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# SUBSONIC PERFORMANCE POTENTIAL OF RAMJETS AND EJECTOR RAMJETS

William E. Supp, et al

Air Force Aero Propulsion Laboratory
Wright-Patterson Air Force Base, Ohio

May 1972

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*WILLIAM E. SUPP*

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*JOHN H. MILLER*

TECHNICAL REPORT AFAPL-TR-72-7



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98

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# FOREWORD

This report was prepared by the Ramjet Applications Branch of the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The work described was accomplished under Task 301211, "Ramjet Design and Assessment," of Project 3012, "Ramjet Technology," and represents work accomplished from December 1970 to September 1971. The Project Engineer for this work was W. E. Supp.

This report was submitted by the authors January 1972.

This technical report has been reviewed and is approved.

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# ABSTRACT

A method for analyzing the performance of a ramjet engine at subsonic flight speeds is presented. The absence of a known choked point (M=1) in the engine necessitates an iterative solution. A modified ideal gas analysis is utilized. Considered are the conventional ramjet with liquid fuel injection and an ejector ramjet using vaporized fuel injected into the engine at supersonic velocities. In the latter case, the fuel's momentum is significant and the ejector action draws additional air mass into the engine, which must be considered in the analysis. The method presented compares the two engine cycles at several subsonic flight speeds for both JP-4 and propane fuel. The effects of several levels of component efficiencies are considered.

TABLE OF CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (CONTD)

## SYMBOLS

| SYMBOL | EXPLANATION |
|---|---|
| $A$ | area, $ft^2$ |
| $A_c$ | inlet cowl area, $ft^2$ |
| $C_{DB}$ | burner drag coefficient |
| $C_F$ | thrust coefficient, $F/q_oA_3$ |
| $C_{FN}$ | thrust coefficient with additive drag, $^{FN}/q_oA_3$ |
| $\bar{C}_P$ | pressure coefficient for diffuser |
| $F$ | net internal thrust, $lb_f$ |
| $F_N$ | net internal thrust minus additive drag, $lb_f$ |
| $f/a$ | fuel-to-air mass ratio |
| $g_c$ | conversion factor = 32.17405 lbm ft/$lb_f$ $sec^2$ |
| $Isp$ | fuel specific impulse, $^{lbf}/_{lbm}/hr.$ |
| $Isp_N$ | fuel specific impulse with additive drag, $^{lbf}/_{lbm}/hr.$ |
| $\dot{m}$ | mass rate of flow, lbm/sec |
| $M$ | mach number |
| $M_N$ | molecular weight, $\frac{lbm}{lbm\text{-}mole}$ |
| $N_D$ | dump pressure loss exponent |
| $P$ | pressure, $lbf/ft^2$ |
| $P_T$ | total pressure, $lbf/ft^2$ |
| $\overline{P}$ | stream thrust, $lb_f$ |
| $q_o$ | free stream dynamic pressure, $lbf/ft^2$ |
| $R°$ | universal gas constant = 1545 $\frac{ft\text{-}lbf}{lb_m\text{-}mole - °R}$ |
| $T$ | temperature, °R |
| $T_T$ | total temperature, °R |

## SYMBOLS (CONTD)

| SYMBOL | EXPLANATION |
|---|---|
| $(\Delta T_T)$ actual | combustor actual total temp. rise, °R |
| $(\Delta T_T)$ ideal | combustor ideal total temp. rise, °R |
| u | velocity, ft/sec |
| X | X function — See Section III |
| Y | Y function — See Section III |
| Z | Z function — See Section III |
| $\gamma$ | ratio of specific heats |
| $\eta_c$ | combustion efficiency = $(\Delta T_T)$ actual/$(\Delta T_T)$ ideal |
| $\rho$ | density; lbm/ft$^3$ |

SUBSCRIPTS

| | |
|---|---|
| 0 - 5 | engine stations (see Figures 1 and 2) |
| P | ejector ramjet primary chamber |
| * | ejector ramjet primary nozzle throat |
| C | ejector ramjet primary nozzle exit |
| T | total conditions |

# SECTION I
# INTRODUCTION

The purpose of this report is to analyze the performance of two ramjet engine cycles operating at subsonic flight conditions. One is a conventional liquid-fueled ramjet and the other is an ejector ramjet that uses gaseous propane. Both JP-4 and liquid propane conventional ramjets are considered. The ejector ramjet introduces its fuel at supersonic velocities with a momentum high enough that it might increase the cycle pressure ratio and overall engine performance over that obtainable in the conventional ramjet. The magnitude of this performance is determined on an ideal cycle basis.

In this report, three types of engines are analyzed (see Table I): (1) a propane-fueled ejector ramjet; (2) a propane-fueled ramjet; and (3) a JP-4-fueled ramjet. Several efficiency levels for each type of engine are considered.

First, each engine is assumed to have no internal losses such as burner drag, combustion efficiency losses, diffuser losses, or friction losses. These results establish the basic trends and serve to determine the maximum values possible for the performance variables. This "no loss" case is referred to as the ideal case.

Secondly, component efficiencies are applied equally to all three engines. Baseline values of these component efficiencies were considered to be representative state-of-the-art values for a subsonic, JP-4

fueled ramjet engine; values used were a burner drag coefficient of 4.0 and a combustion efficiency of 90%. These results establish practical performance estimates for the JP-4 ramjet and compare them with those of propane-fueled engines having equal component efficiencies.

Instead of using a burner drag coefficient, we applied anothe efficiency factor to the ejector ramjet. Since the ejector ramjet uses the dump into the combustion chamber as the flame-holding device and does not have a baffle type flameholder, the burner drag of 4.0 was replaced with an estimated dump loss correction based on experimental results (Reference 5). Since the ejector ramjet has a diffuser section ahead of the dump, experimental corrections (References 3 and 4) were applied to the flow to account for this diffuser loss.

Most of the above mentioned parametrics were computed assuming variable inlet size and, therefore, do not consider additive drag effects. Several select cases have been corrected for additive drag to demonstrate the order of magnitude of the additive drag correction. The same exit-to-combustor-area ratio of 0.55 is used for all three engines.

A computer program was written to calculate the performance of these engine cycles. The method is described in Section III. Appendixes I and II describe the computer program.

TABLE I

CYCLES INVESTIGATED

| CYCLE | COMPONENT LOSSES |
|---|---|
| PROPANE-FUELED EJECTOR RAMJET | |
| Cycle 1 | No Losses |
| Cycle 2 | $C_{D_B}$ = 4 and $\eta_c$ = 90% |
| Cycle 3 | $C_p$ = 0.51, $N_D$ = 0.25 and $\eta_c$ = 90% |
| PROPANE-FUELED RAMJET | |
| Cycle 1 | No Losses |
| Cycle 2 | $C_{D_B}$ = 4 and $\eta_c$ = 90% |
| JP-4-FUELED RAMJET | |
| Cycle 1 | No Losses |
| Cycle 2 | $C_{D_B}$ = 4 and $\eta_c$ = 90% |

# SECTION II

# DESCRIPTION OF CYCLES

## 1. THE RAMJET CYCLE

The conventional ramjet engine has been described and analyzed many times in the literature, and this basic treatment will not be repeated here. The majority of these treatments consider the ramjet at supersonic flight speeds with a choked exit nozzle, which presents a convenient station to begin analysis. The ramjet operating at subsonic flight speeds, however, usually has no choked station throughout the entire engine. Figure 1 presents a schematic of such an engine and defines the engine station nomenclature. A convergent nozzle is usually employed and, since the internal flow is entirely subsonic, pressure changes at any station are felt throughout the engine. The mass flow entering the engine will adjust itself, generally, so that the static pressure at the exit (Station 5) is equal to the ambient pressure. There are a few cases at high subsonic flight speeds where Station 5 can be choked with $P_5 > P_0$.

For the purposes of this analysis, an ideal inlet was considered so as to facilitate the presentation of data in parametric form. Also, no capture area was specified. Therefore, ideal one-dimensional flow is considered between Station 0 and Station 3. The results thus present the net jet thrust coefficient. A known capture area can be imposed and the data presented can be corrected for additive drag between Station 0 and Station 1. This was done for selected cases to describe the method.

Component losses can be considered if desired. Total pressure losses due to friction or flameholders in the combustor are defined by a burner drag coefficient, to be defined in the next section. A combustion efficiency based on burner ideal total temperature rise can be specified, if desired. The nozzle is considered ideal and no losses are defined. Fuel is considered to be injected at room temperature. The fuel mass is considered in the continuity equation, but its momentum is neglected.

The analysis procedure was chosen to facilitate rapid calculation and convergence on digital computer facilities. Component efficiencies, engine geometries, fuel/air ratio, and flight conditions are assumed. An initial estimate of the free stream area (or mass flow) is made and the properties at each station throughout the engine, from Station 0 to Station 5, are calculated. The static pressure at Station 5 is compared with the ambient static pressure of the known flight condition. These must be equal for a practical solution (except for the one exception where the exit nozzle is choked). If these pressures do not match, the estimated value of $A_0$ is modified and the calculations are repeated. When this matching of static pressures has been achieved, the engine performance parameters (thrust coefficient and specific impulse) are calculated.

## 2. THE EJECTOR RAMJET CYCLE

The analysis of the ejector ramjet is similar to that of the ramjet except in the treatment of the fuel addition. A schematic of the ejector ramjet is shown in Figure 2. A fuel injector in the form of a primary rocket with a C/D nozzle is located at Station 1. Fuel is heated to vaporization and is then introduced into the primary. This

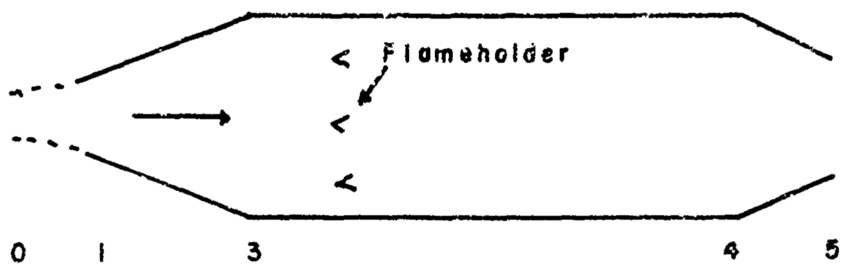


Figure 1. Ramjet Engine

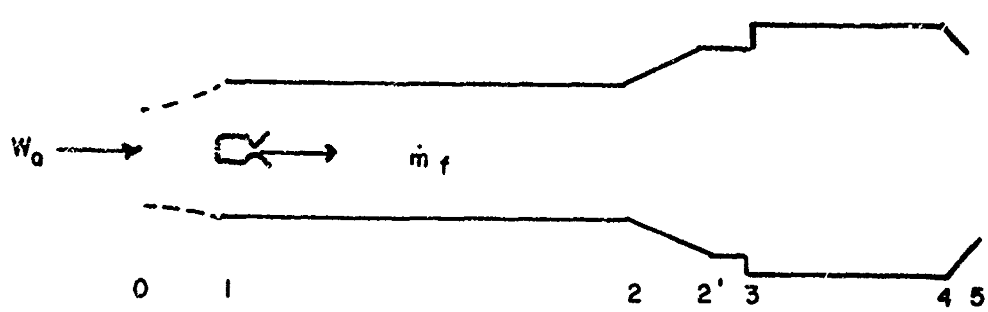


Figure 2. Ejector Ramjet Engine

fuel is gaseous at high pressure and elevated temperature. The fuel expands in the C/D nozzle at supersonic velocities, with a momentum significantly high to be considered in the cycle. The fuel and air mix between Stations 1 and 2 without burning. The mixed stream then enters the combustor through a diffuser and sudden dump. This area change serves as a flameholding device to sustain combustion. The rocket primary acts as an ejector and draws additional air into the engine. The momentum of the primary increases the cycle total pressure ratio over that of a conventional ramjet.

Component losses through the engine can be considered in two ways. A burner drag coefficient can be applied to correct for all pressure losses, as was done for the conventional ramjet. The losses associated with the diffusion and sudden dump can be considered separately as a function of the geometry with correlations to be described in the next section. A combustion efficiency based on the burner ideal total temperature rise can be specified if desired. Incomplete mixing of the fuel and the air in the mixing tube will result in less ejector action and less mass flow through the engine than the ideal case.

A provision is incorporated to account for these estimated losses. The method chosen is to arbitrarily reduce the primary momentum by some percentage to obtain a reduced pressure level at the end of the mixing tube (Station 2). This method was chosen for ease in computer programming and results in a converged air mass flow less than that obtained from the ideal ejector ramjet but still more than that possible from the conventional ejector ramjet at the same condition. The component losses can be applied to

the degree necessary to reduce ideal ejector performance to the level corresponding to actual test data. Mixing losses were not considered in the study results presented in this report.

# SECTION III

# ANALYSIS PROCEDURES

## 1. GENERAL

The ramjet and ejector ramjet cycles can be analyzed using constant gamma, ideal gas equations. It is a requirement for subsonic engines that the pressure at the exit of the nozzle be equal to the free stream pressure. It is therefore the purpose of the cycle analysis to find the air flow through the engine which will allow the nozzle exit pressure to match the free stream pressure for the given engine parameters. To calculate the nozzle exit pressure, it is necessary to calculate the Mach number and pressure at each station of the engine beginning at the inlet. There is one exception to the above criteria. If the nozzle is choked the exit pressure can be greater than or equal to ambient pressure

The Mach functions X, Y, and Z will be used to simplify the analysis procedure in this report. The following is a brief discussion of these functions. The equations of continuity, and momentum and energy are used to relate the conditions at one engine station to another. The continuity equation in its simplest form states that the mass flow rate at Station i is equal to the mass flow rate at Station i+1. This is written

$$\dot{m}_i = \dot{m}_{i+1} + \dot{m}_{added} \qquad (1)$$

Using the ideal gas law $\rho = \dfrac{PM_W}{RT}$

and the following relationships

$$\dot{m} = \rho A V$$

$$\frac{T_T}{T} = 1 + \frac{\gamma - 1}{2} M^2$$

$$\frac{P_T}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

Equation 1 can be written

$$\left. \frac{P_T\, A M}{\sqrt{T_T}} \sqrt{\gamma \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma + 1}{1 - \gamma}}} \sqrt{\frac{g_c\, M_w}{R}} \right]_i$$

$$= \left. \frac{P_T\, A M}{\sqrt{T}} \sqrt{\gamma \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma + 1}{1 + \gamma}}} \sqrt{\frac{g_c\, M_w}{R}} \right]_{i+1}$$

$$+ \dot{m} \ \text{added}$$

This equation is simplified by defining

$$X = M \sqrt{\gamma \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma + 1 / 1 - \gamma}}$$

This gives the final form of the continuity equation

$$\left[\frac{P_T\, A X}{\sqrt{T_T}} \sqrt{\frac{g_c\, M_w}{R}}\right]_i = \left[\frac{P_T\, A X}{\sqrt{T_T}} \sqrt{\frac{g_c\, M_w}{R}}\right]_{i+1} + \dot{m} \ \text{added} \qquad (2)$$

The momentum equation for a frictionless, constant area duct is

$$\left[\frac{\dot{m} u}{g_c} + PA\right]_i = \left[\frac{\dot{m} u}{g_c} + PA\right]_{i+1}$$

This equation can be expanded in a manner similar to the continuity equation to give

$$\left[P_T\, A\, Z\right]_i = \left[P_T\, A\, Z\right]_{i+1} \tag{3}$$

where Z is defined as

$$Z = \frac{1+\gamma M^2}{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}}$$

The quantity $P_T A Z$ is called stream thrust and is denoted by the symbol $\bar{P}$. If the continuity and momentum equations are combined, the following equation is obtained

$$\bar{P} = \frac{\dot{m}\sqrt{T_T}}{Y}\sqrt{\frac{R}{g_c\, M_w}} \tag{4}$$

where

$$Y = \frac{X}{Z}$$

Equations 2, 3, and 4 are used to calculate the flow conditions through the inlet. A complete explanation of these equations is given in Reference 2. The Mach number functions X, Y, and Z are used to determine the Mach number.

In this study, all engine areas and the fuel/air ratio are assumed known, as well as the free-stream temperature, pressure, and Mach number.

The ideal temperature rise in the combustor, the molecular weight, and the gamma at the exit of the combustor are tabulated as a function of the air total temperature and the fuel/air ratio. Values of combustion efficiency, $\eta_C$, and burner drag coefficient, $C_{DB}$, were assumed to permit us to evaluate their effect on engine performance.

The combustion efficiency is defined as

$$\eta_c = \frac{(\Delta T_T)_{actual}}{(\Delta T_T)_{ideal}}$$

The burner drag coefficient is defined as

$$C_{DB} = \frac{\overline{P_3} - \overline{P_4}}{\frac{1}{2} \gamma_3 A_3 M_3^2 P_3}$$

where the term $\bar{P}_3 - \bar{P}_4$ is the drag loss caused by the flameholder.

## 2. RAMJET ANALYSIS

The ramjet analysis consisted of the following: First we assumed an inlet capture area. Then we used the continuity equation to calculate the conditions at the entrance to the combustor, and the momentum and continuity equations to calculate the conditions at the exit of the combustor. Finally, we used the continuity equation to relate the condition at the exit of the combustor to the conditions at the exit of the nozzle.

The method of analysis is as follows:

(a) Assume an $A_0$.

(b) From continuity, calculate the Mach number at Station 3. Assuming the inlet isentropically diffuses the air and the value of gamma at both stations is 1.4, then

$$X_3 = X_0 \frac{A_0}{A_3}$$
$$M_3 = f(X_3)$$

(c) Calculate the free-stream total pressure.

$$P_{T0} = P_0 \left(1 + \frac{\gamma_0 - 1}{2} M_0^2\right)^{\frac{\gamma_0}{\gamma_0 - 1}}$$

Since isentropic diffusion has been assumed in the inlet, it follows that

$$P_{T3} = P_{T0}$$

(d) Calculate the mass flow rate of air

$$\dot{m}_A = P_0 A_0 M_0 \sqrt{\frac{\gamma_0 \, g_c \, M_{w0}}{R \; T_0}}$$

(e) From the given fuel/air ratio, calculate the fuel flow rate.

$$\dot{m}_f = \dot{m}_A \;\; f/a$$

(f) Calculate the Mach number at Station 4 from the continuity and momentum equations.

$$Y_4 = \frac{Y_3}{1 + f/a} \sqrt{\frac{M_{w0}}{M_{w4}} \left[1 + \eta_c \frac{(T_{T4} - T_{T0})}{T_{T0}}\right]} \; \frac{1 + \gamma M_3^2}{\left[1 + \gamma M_3^2 \left(1 - \frac{1}{2} C_{DB}\right)\right]}$$

$$M_4 = f(Y_4)$$

(g) Calculate the total pressure at Station 4 from the momentum equation.

$$P_{T4} = P_{T3}\left[\frac{z_3}{z_4} - \frac{1}{2} C_{DB} \frac{\gamma_2 M_3^2}{z_4} \frac{P_3}{P_{T_3}}\right]$$

(h) Calculate the Mach number at Station 5 from the continuity equation. It is assumed that the values of gamma, total temperature, and total pressure at Station 5 are the same as those at Station 4.

$$X_5 = X_4 \frac{A_4}{A_5}$$

$$M_5 = f(X_5)$$

(i) Calculate the static pressure at Station 5.

$$P_5 = \frac{P_{T_4}}{\left(1 + \frac{\gamma_4 - 1}{2} M_5^2\right)^{\gamma_4/\gamma_4 - 1}}$$

(j) Compare the static pressure at Station 5 with the ambient pressure $P_0$. If these pressures do not compare reasonably well, adjust $A_0$ and return to Step b. If

$P_5 > P_0$, increase $A_0$

$P_5 < P_0$, decrease $A_0$

Once the pressures have be .n satisfactorily matched, the engine performance can be calculated.

(k) Thrust = $P_{T4}\ A_5\ Z_5 - P_{T0}\ A_0\ Z_0 - P_0\,(A_5 - A_0)$

Isp = thrust/$\dot{m}_f$

Note: If the Mach number at any station exceeds one, reduce $A_0$ and return to Step (b). If the Mach number at Station 5 equals one and $P_5 \geq P_0$, this is a solution.

## 3. EJECTOR RAMJET ANALYSIS

The ejector ramjet was analysed in a manner similar to the ramjet. In addition to burner drag and combustion efficiency, ejector effectiveness, diffuser and dump loss were also considered. Integration of the ejector into the ramjet cycle analysis is the only major deviation from the previous analysis.

The method of analyzing the ejector ramjet is as follows:

(a) Assume a value for $A_0$.

(b) From the continuity equation, calculate the Mach number at Station 1, assuming the inlet isentropically diffuses the air, and the value of gamma at both stations is 1.4.

$$X_1 = X_0 \frac{A_0}{A_1}$$

$$M_1 = f\ (X_1)$$

(c) Calculate the ree stream total pressure

$$P_{T_0} = P_0 \left(1 + \frac{\gamma_0 - 1}{2} M_0^2\right)^{\frac{\gamma_0}{\gamma_0 - 1}}$$

Since isentropic diffusion has been assumed in the inlet, it follows that

$$P_{T1} = P_{To}$$

(d) Calculate the air stream thrust at Station 1 from the momentum equation.

$$\bar{P}A_1 = P_{To} \; A_1 \; Z_1$$

(e) Calculate the mass flow rate of air.

$$\dot{m}_A = P_o \; A_o \; M_o \sqrt{\frac{\gamma_o \; g_c \; M_w}{R \;\; To}}$$

(f) From the given fuel/air ratio, calculate the fuel flow rate.

$$\dot{m}_f = \dot{m}_A \;\; f/a$$

(g) Calculate the total pressure of the fuel injector assuming a choked throat. In this analysis the ejector geometry is fixed; therefore, the ejector total pressure is varied to match the flow rate.

$$P_{TP} = \frac{\dot{m}_f}{A_* X_*} \sqrt{\frac{T_{Tf} \; R}{g_c \; M_w}}$$

where $A*$ = area of injector throat

$X*$ = X function at throat

$T_{Tf}$ = total temperature of fuel

(h) Calculate the Mach number at the exit of the injector.

$$X_e = \frac{X_* \; A_*}{A e}$$

$$M_e = f \; (X_e)$$

(i) Calculate the stream thrust at the ejector exit.

$$\bar{P}_e = P_{TP} A_e Z_e$$

(j) Calculate the temperature, molecular weight, and gamma of the mixed fuel and air at Station 2 by mass averaging the individual properties. The individual physical properties are obtained from tables of data or empirical correlations.

(k) Calculate the stream thrust at Station 2 from the momentum equation. For the ideal case

$$\bar{P}_2 = \bar{P}_1 + \bar{P}_e$$

If it is desired to account for inefficiency of the ejector action, a component efficiency can be incorporated. For example

$$\bar{P}_2 = \bar{P}_1 + \eta \bar{P}_e$$

(l) Calculate the Mach number at Station 2, from the continuity and momentum equations.

$$Y_2 = \frac{\dot{m}_A \dot{m}_f}{F_2} \sqrt{\frac{T_{T_2} R}{g_c M_{w_2}}}$$

$$M_2 = f(Y_2)$$

(m) Calculate the total pressure at Station 2 from the momentum equation.

$$P_{T_2} = \frac{\bar{P}_2}{A_2 \quad Z_2}$$

(n) Calculate the static pressure at Station 2.

$$P_2 = P_{T2}\left(1 + \frac{\gamma_2 - 1}{2} M_2^2\right)^{\frac{\gamma_2}{1-\gamma_2}}$$

(o) Calculate the static pressure at Station 2' if diffuser losses are to be considered

$$P_2' = \left(\frac{1}{2}\bar{C}_p \gamma_2 M_2^2 + 1\right) P_2$$

where $\bar{C}_p$ is an experimentally determined diffuser loss factor obtained from References 3 and 4. If isentropic diffusion is assumed

$$P_2' = P_2$$

(p) Calculate the Mach number at Station 2' using the continuity equation.

$$M_2' = \left[\frac{-1 \pm \sqrt{1 + \frac{2(\gamma_2 - 1)(\dot{m}_A + \dot{m}_f) R T_{T2}}{P_2'^2 A_2'^2 \gamma_2 g_c M_w}}}{\gamma_2 - 1}\right]^{\frac{1}{2}}$$

(q) Calculate the total pressure after the dump at Station 3, by using the following equation:

$$P_{T3} = P_2'\left[\left(1 + \frac{\gamma_2 - 1}{2} M_2'^2\right)^{\frac{\gamma_2}{\gamma_2 - 1}}\right] e^{\left(-\frac{1}{2} N_D \gamma_2 M_2'^2\right)}$$

where $N_D$ is obtained from Reference 5.

(r) Calculate the Mach number after the dump at Station 3.

$$X_3 = \frac{(\dot{m}_A + \dot{m}_f)}{P_{T3} A_3} \sqrt{\frac{R \quad T_{T2}}{g_c \quad M_{w2}}}$$

$$M_3 = f\ (X_3)$$

(s) Calculate the static pressure at Station 3.

$$P_3 = P_{T3} \left(1 + \frac{\gamma_2 - 1}{2} M_3^2\right)^{\frac{\gamma_2}{1-\gamma_2}}$$

(t) Calculate the Mach number at Station 4 from the continuity and momentum equat ons.

$$Y_4 = Y_3 \sqrt{\frac{M_{w2}}{M_{w4}} \left[1 + \frac{\eta_c (T_{T4} - T_{T2})}{T_{T2}}\right]} \quad \frac{1 + \gamma M_3^2}{\left[1 + \gamma M_3^2 (1 - Y_2 C_{DB})\right]}$$

$$M_4 = f\ (Y_4)$$

(u) Calculate the total pressure at Station 4 from the momentum equation.

$$P_{T4} = P_{T3} \left[\frac{Z_3}{Z_4} - \frac{1}{2} C_{DB} \gamma_2 \frac{M_3^2}{Z_4} \frac{P_3}{P_{T3}}\right]$$

(v) Calculate the Mach number at Station 5 from the continuity equation. It is assumed that the values of gamma, total temperature, and total pressure at Station 5 are the same as those at Station 4.

$$X_5 = X_4 \frac{A_4}{A_5}$$

$$M_5 = f(X_5)$$

(w) Calculate the static pressure at Station 5.

$$P_5 = P_{T_4} \left(1 + \frac{\gamma_4 - 1}{2} M_5^2\right)^{\frac{\gamma_4}{1-\gamma_4}}$$

(x) Compare the static pressure at Station 5 with the ambient pressure $P_0$. If these pressures do not compare reasonably well, adjust $A_0$ and return to Step (b).

(y) If the static pressure and $P_0$ match,

Thrust = $P_{T4} A_5 Z_5 - P_{T0} A_0 Z_0 - P_0 (A_5 - A_0)$

Isp = thrust/$\dot{m}_f$

Note: If the Mach number at any station exceeds one, reduce $A_0$ and return to Step (b). If the Mach number at Station 5 equals one and $P_5 \geq P_0$, this is a solution.

# SECTION IV
# STUDY RESULTS

## 1. IDEAL PROPANE EJECTOR RAMJET

Figure 3 presents the parametric performance data for a propane fueled subsonic ejector ramjet at an altitude of 23,000 feet, $A_5/A_3$ = 0.55, and 100% efficiencies. Plotted is the thrust coefficients ($C_F$) based on free stream dynamic pressure and combustor area versus fuel specific impulse (ISP). The dashed lines represent constant values of fuel-to-air ratio and the solid lines represent constant values of free stream Mach number. Several factors are evident from this figure. First, it is noted that for this ideal case, as the fuel-air ratio decreases the fuel specific impulse continues to increase while the thrust decreases. Obviously, the specific impulse must maximize at some f/a ratio and then decrease as f/a ratio is lowered further. This will be evident when component efficiencies are introduced into the cycle. The second prominent feature occurs above the stoichiometric fuel/air ratio (f/a 0.064). As more fuel is added above the stoichiometric point the thrust continues to increase. This phenomenon is not present in the conventional ramjet because the contribution of fuel momentum is not considered in the ramjet cycle. In the ejector ramjet cycle as the fuel flow rate continues to increase the fuel momentum increases and thrust benefits accrue, at a loss in specific impulse. Also, it is noted that specific impulse improves significantly with Mach Number over the range considered.

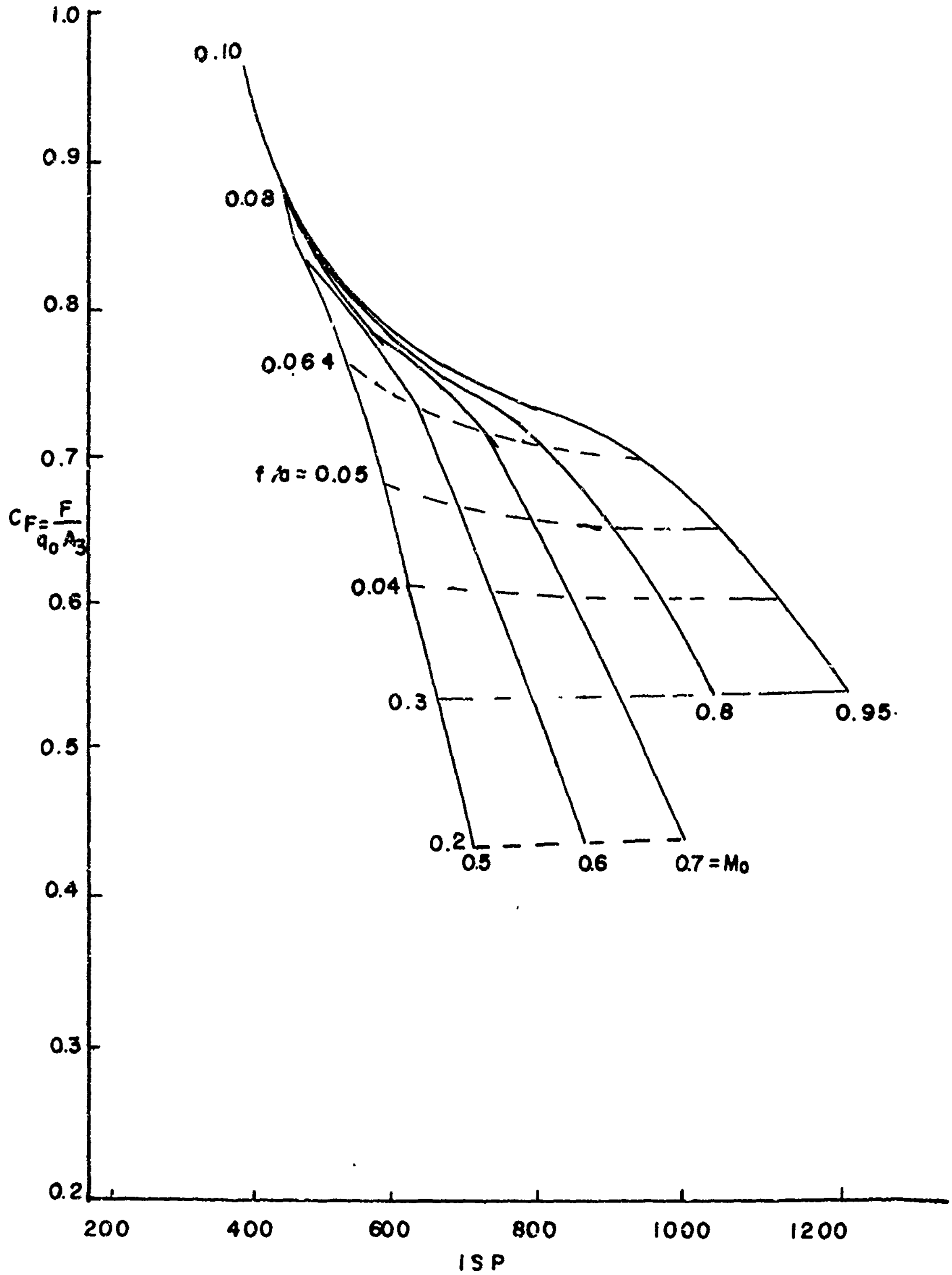


Figure 3. Ideal Ejector Ramjet Performance

2. PROPANE EJECTOR RAMJET ($C_{DB}$ = 4.0, $\eta_c$ = 0.90)

Figure 4 repeats the results of Figure 3 for a propane ejector ramjet except that a burner drag coefficient of 4.0 and a combustion efficiency of 0.90 has been included. If the figures are compared, it can be seen that the performance, both thrust coefficient and specific impulse, have been lowered by including the efficiencies. Also as the fuel-air ratio is decreased the specific impulse does not continue to increase as it did in the ideal case, but maximizes between f/a = 0.02 and 0.03 and decreases as f/a approaches zero. Figure 5 considers additive drag for an engine with $A_c/A_3$ = 0.2047. The design point at which this $A_c/A_3$ was chosen is $M_o$ = 0.95 and $C_F$ = 0.5. Figure 6 is a composite of several constant Mach number lines taken from Figures 4 and 5. The dashed lines in Figure 6 stop a. the line representing full inlet capture. The additive drag effects on engine performance are small in magnitude but increase with increasing Mach number.

3. PROPANE EJECTOR RAMJET (DIFFUSER AND DUMP LOSSES)

It was pointed out previously that the ejector ramjet had a sudden dump into the combustor, which served as a flameholding device; therefore, perhaps the burner drag coefficient of 4.0 used previously was not appropriate. So in an attempt to use component efficiencies consistent with the ejector ramjet geometry, experimental data was obtained to account for the dump loss into the combustor and other data applied to the diffuser directly ahead of the dump. The method of accounting for these effects is described in Section III. A diffuser loss factor $\bar{C}_p$ of 0.51 and a dump loss factor $N_D$ of 0.25 were used instead of a burner drag coefficient. A combustion efficiency of 90%

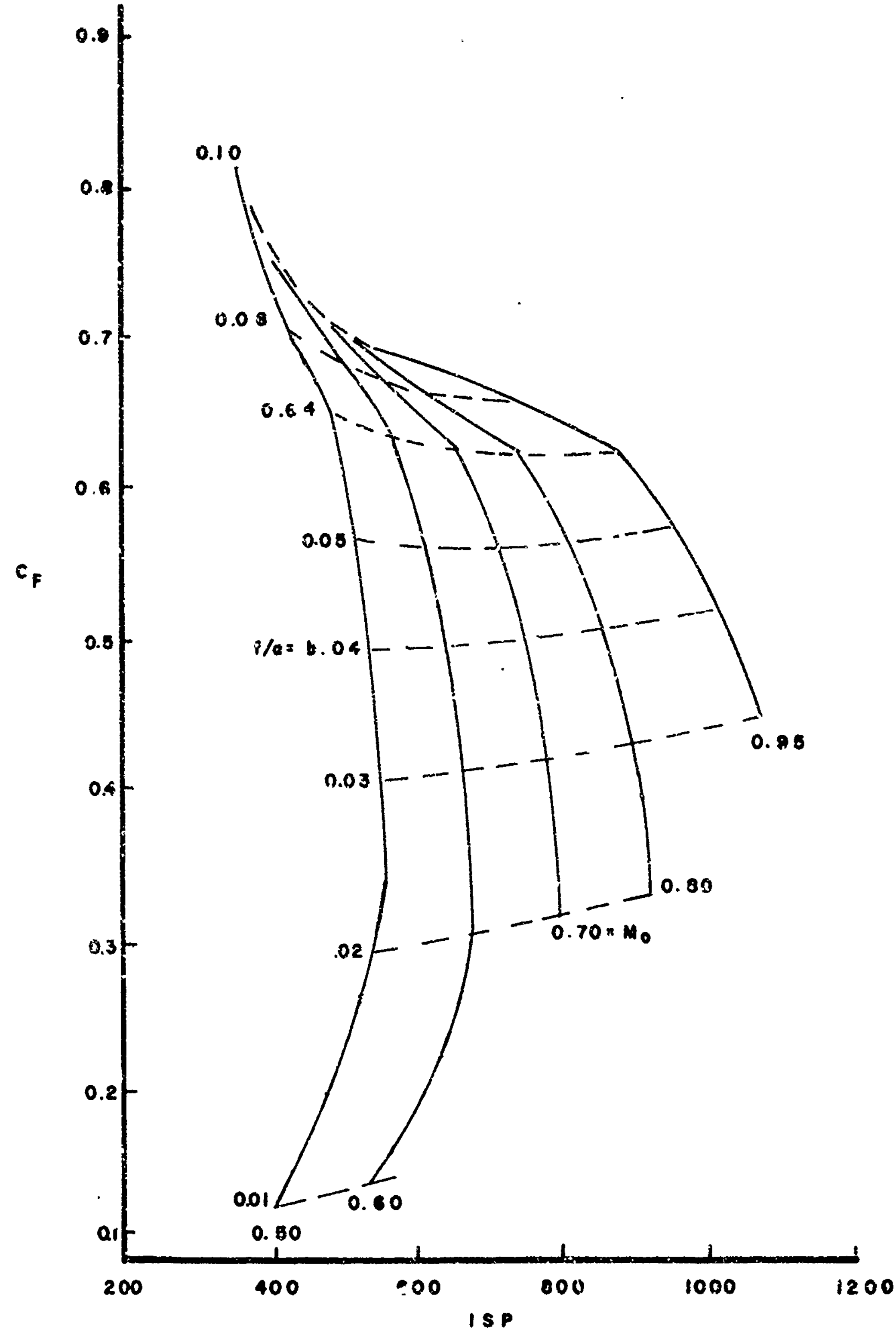


Figure 4. Ejector Ramjet Performance for $C_{D_B}$ = 4 and $\eta_c$ = 90%

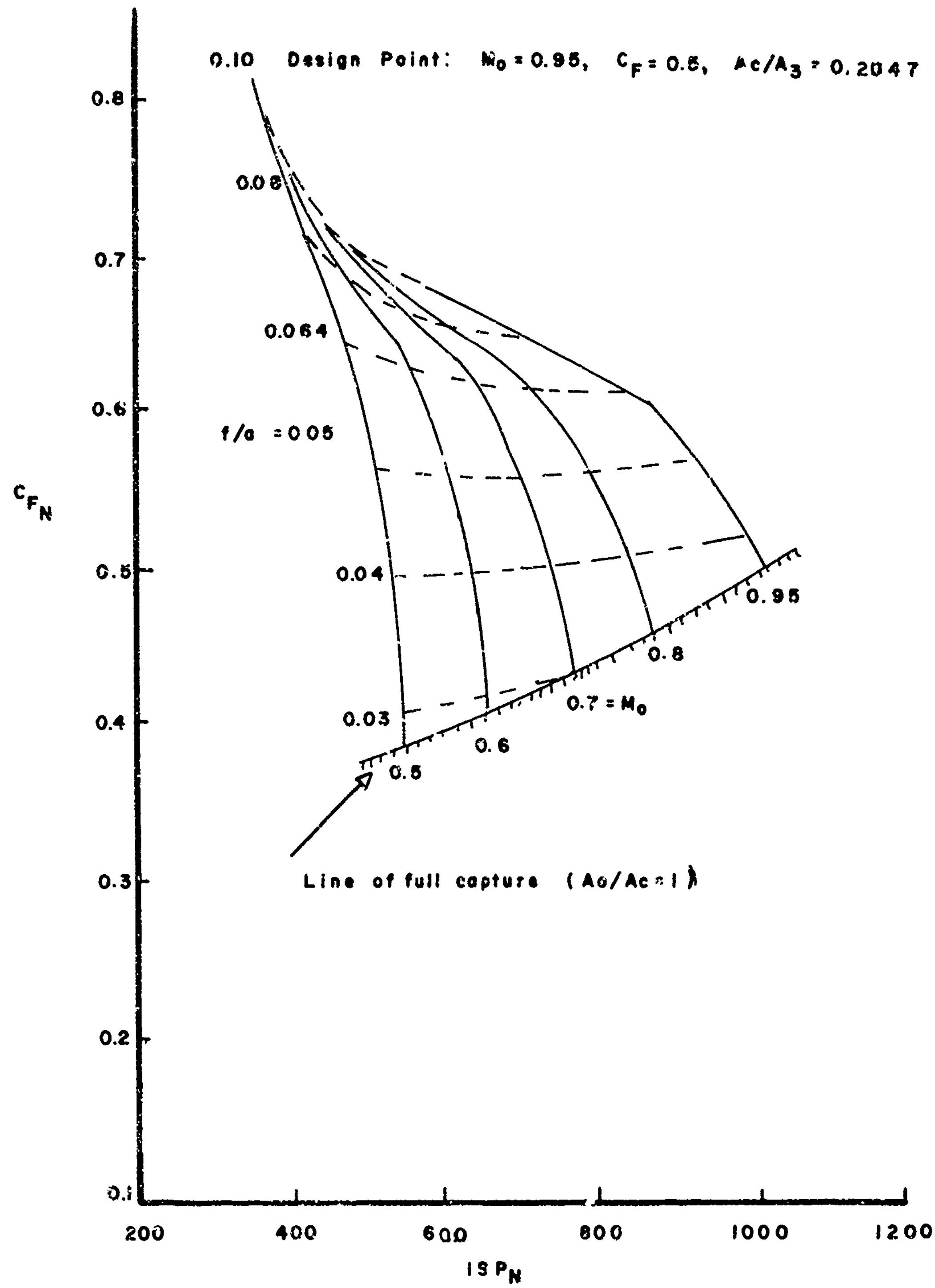


Figure 5 Ejector Ramjet Performance With Additive Drag, $C_{D_B}$ = 4 and $\eta_c$ = 90%

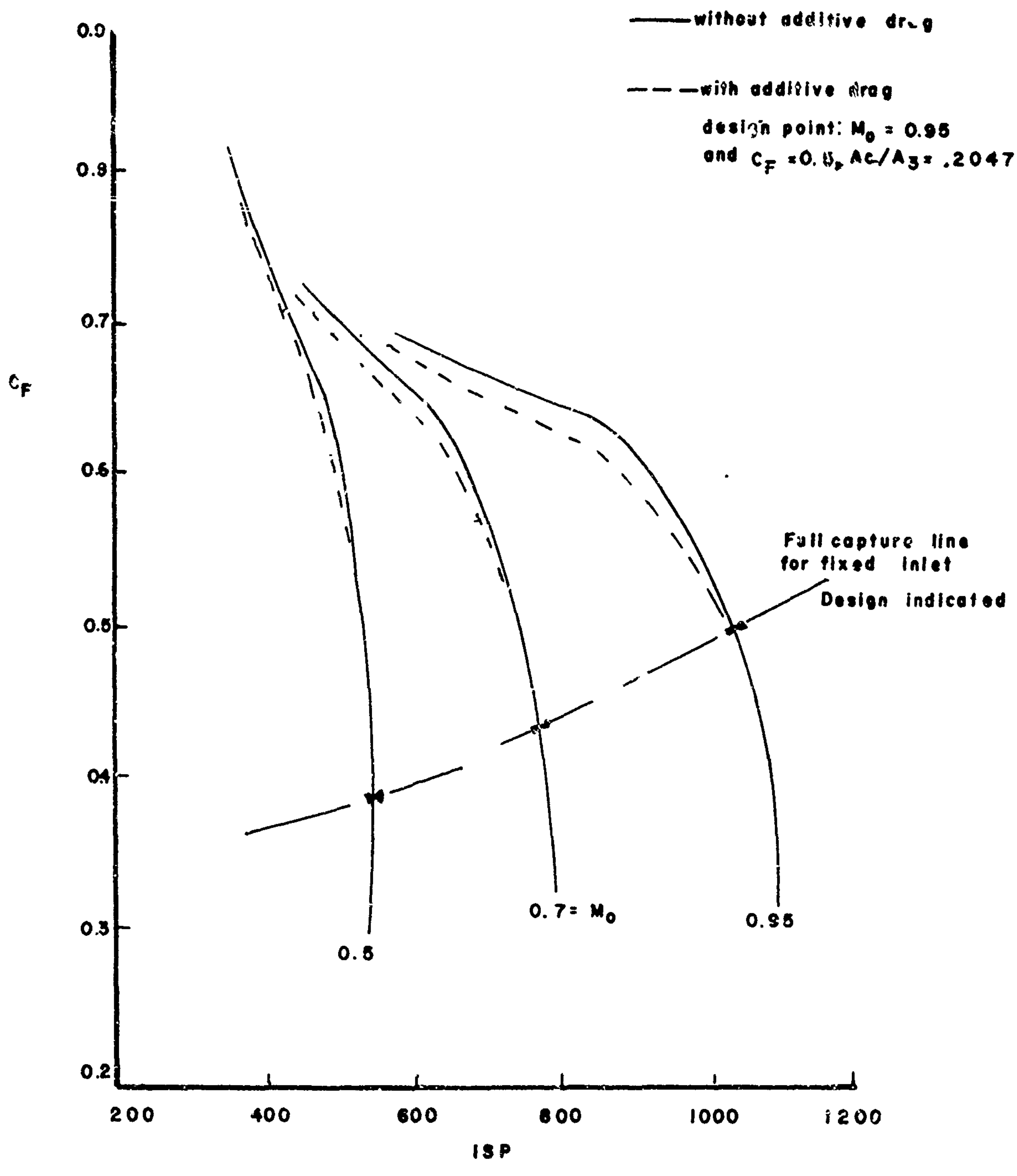


Figure 6. Effects of Additive Drag on Ejector Ramjet Performance With $C_{D_B}$ = 4 and $\eta_c$ = 90%

was maintained. It can be seen from Figure 7 that this case with dump and diffuser loss is worse than the previous case with combustion efficiency of 90% and a burner drag coefficient of 4.0. The absolute values of $\bar{C}_p$ and $N_D$ are for the specific geometry evaluated and apply only to that particular case.

Figures 8 and 9 show the effects of additive drag with an $A_c/A_3 = 0.1825$ which was chosen at the design point corresponding to $M_0 = 0.95$ and $C_F = 0.5$. As was noted for the previous case with $C_{DB} = 4$, the additive drag effects for this case are small.

4. IDEAL PROPANE RAMJET

Figure 10 presents the results for a propane-fueled ramjet with no internal flow losses and an exit area ratio $A_5/A_3$ of 0.55 at 23,000 feet altitude. Figure 10 is a plot of the thrust coefficient versus fuel specific impulse. The same trends are present as for the ejector ramjet (Figure 3) except that above the stoichiometric fuel-air ratio there is no additional increase in the thrust coefficient since fuel momentum is not considered in the ramjet cycle. Thrust coefficient increases with f/a ratio as specific impulse decreases. Here, also, there is no maximization of the specific impulse as the f/a ratio decreases. Again, the specific impulse increases as the subsonic flight speed increases. In general, the ideal ejector ramjet has better performance at fuel/air ratios above approximately 0.025; however, this comparison assumes no internal flow losses for either engine.

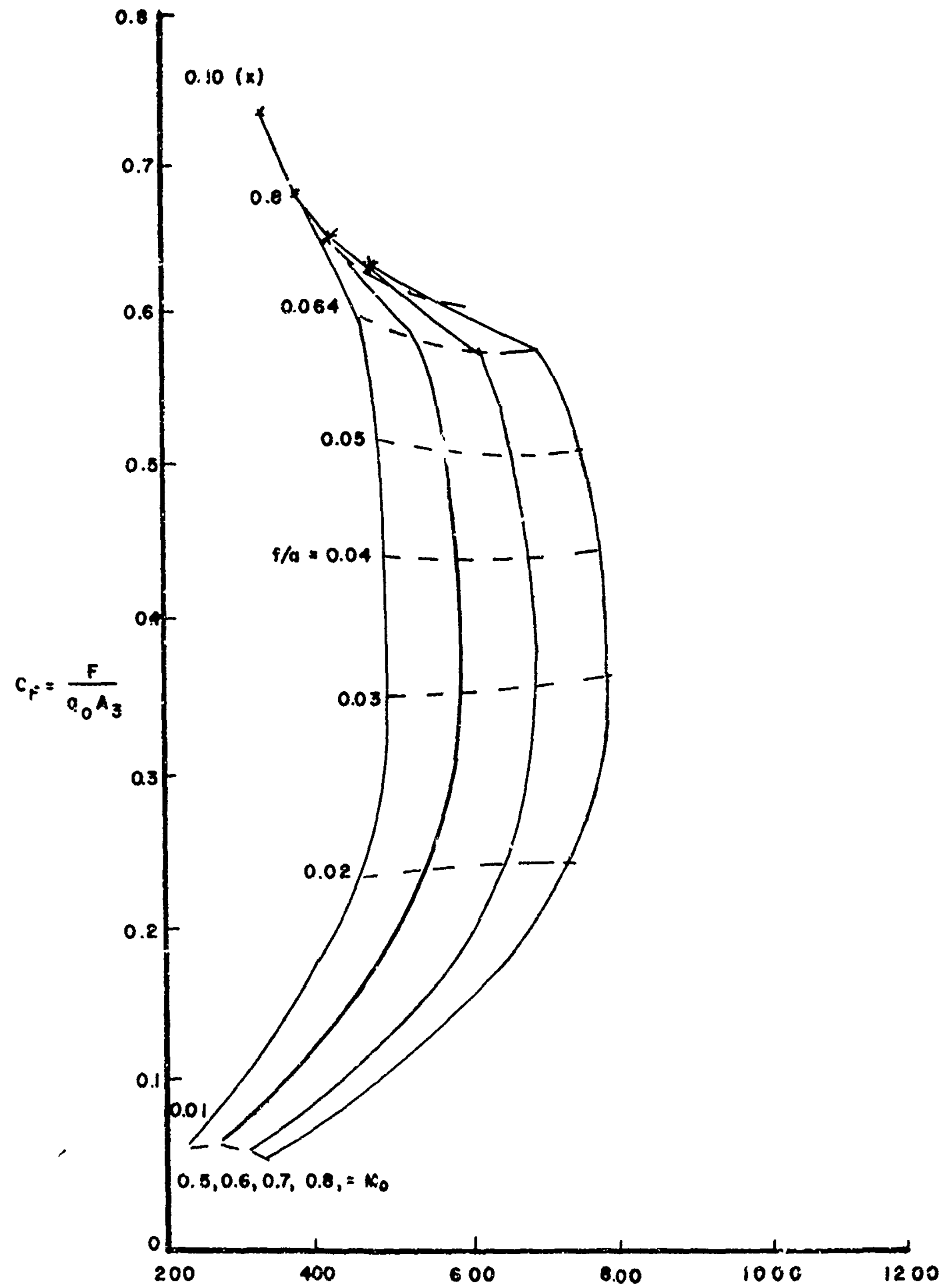


Figure 7. Ejector Ramjet Performance With Diffuser and Dump Losses and $\eta_c$ = 90%

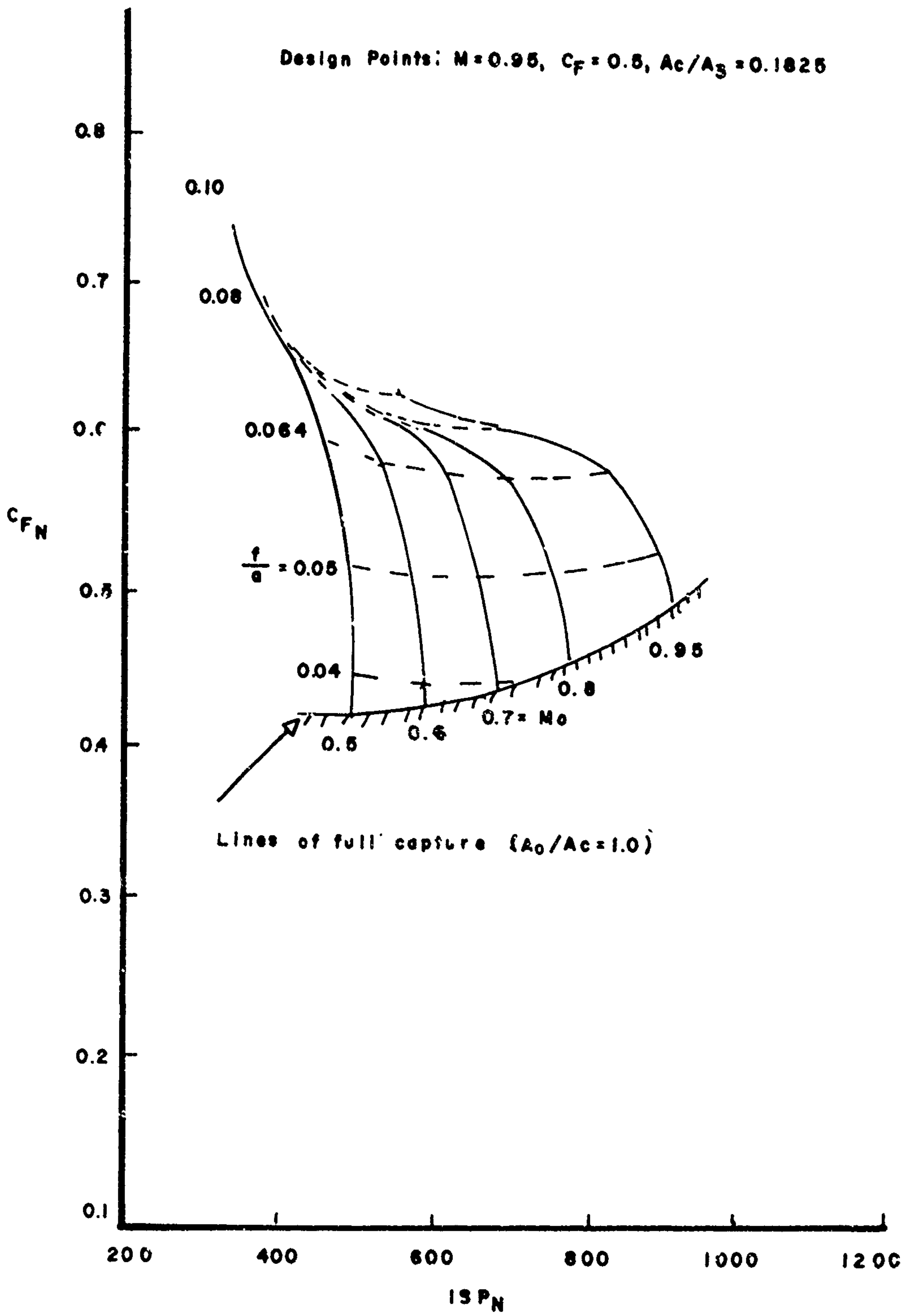


Figure 8. Ejector Ramjet Performance With Additive Drag, Diffuser and Dump Losses, and $\eta_C$ = 90%

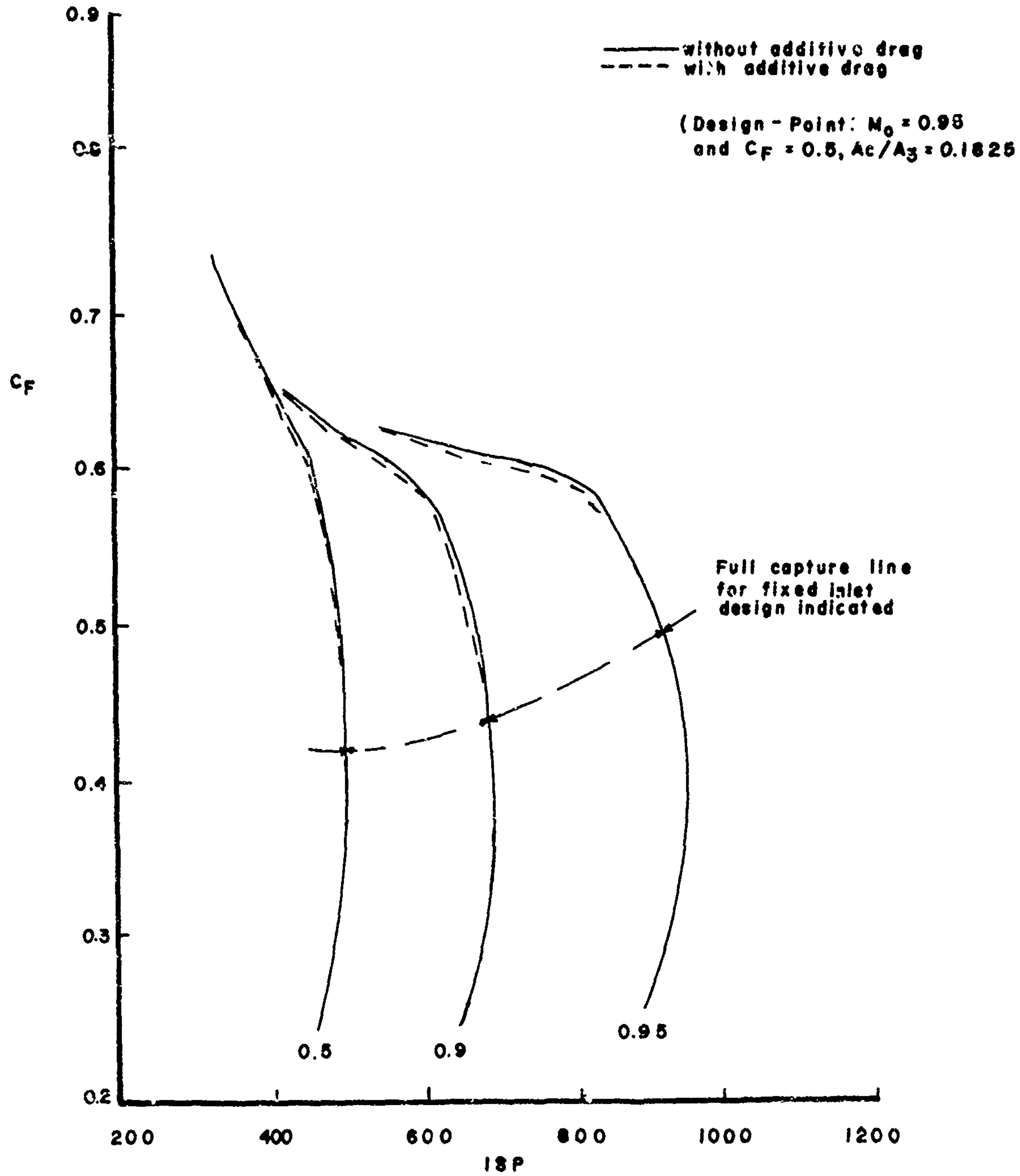


Figure 9. Effects of Additive Drag on Ejector Ramjet Performance With Diffuser and Dump Losses, and $\eta_c$ = 90%

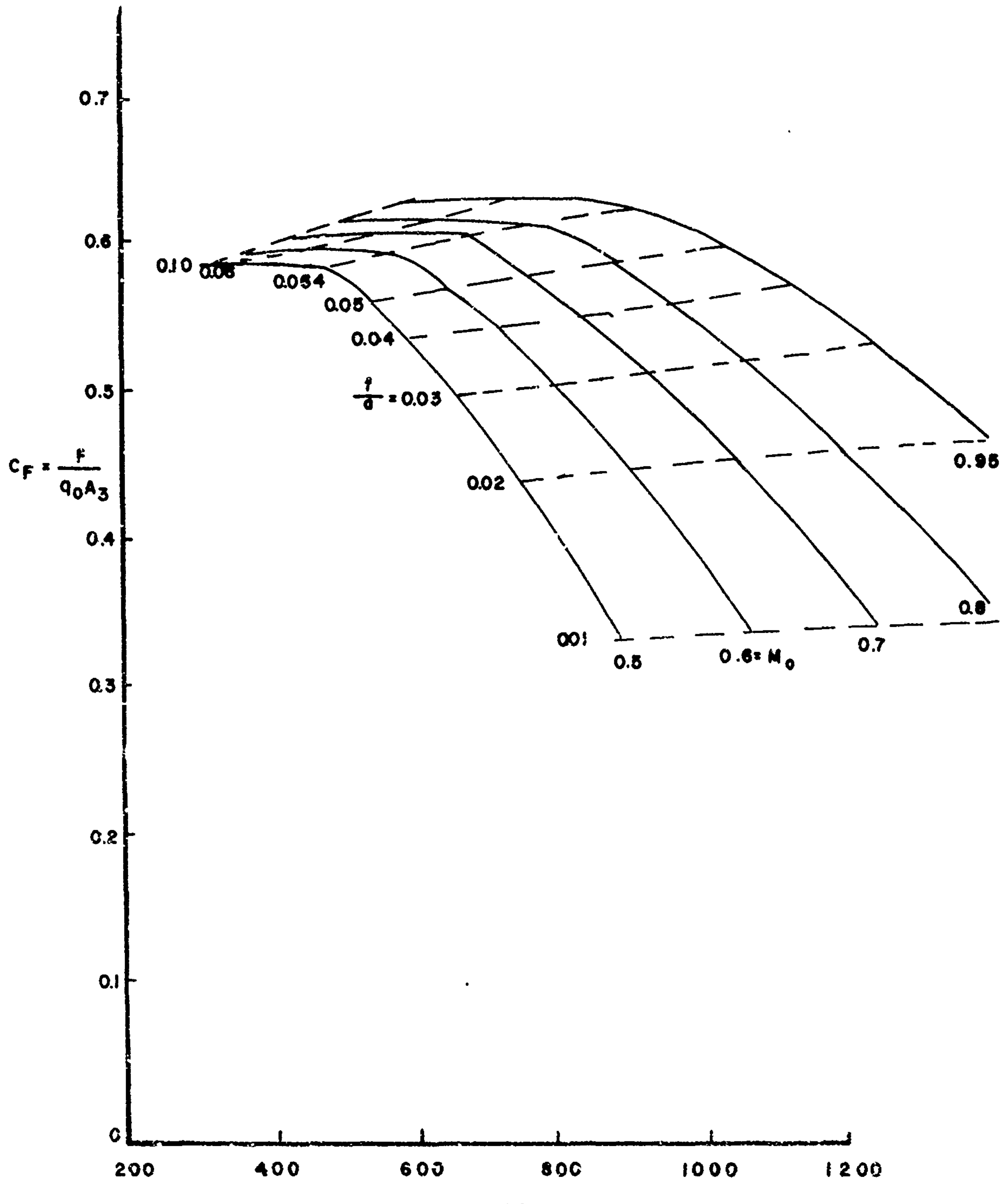


Figure 10. Ideal Propane-Fueled Ramjet Performance

5. PROPANE RAMJET ($C_{DB}$ = 4.0 and $\eta_c$ = 0.90)

Figure 11 presents the results when using a burner drag coefficient of 4.0 and a combustion efficiency of 0.90 for the propane ramjet. They are directly comparable to the ideal case, Figure 10. While the values of thrust and specific impulse are lower for the case with the burner drag and combustion efficiency, the basic trends are the same with the exception of the lower fuel-air ratios. As the fuel-air ratio decreases, the specific impulse does not continue to increase; it maximizes and then decreases as the f/a ratio approaches zero.

6. IDEAL JP-4 RAMJET

Figure 12 presents the ideal performance for a JP-4 fueled engine. This data is similar to the data shown in Figures 10 and 11 for the propane ramjet. Again no internal losses are assumed and $A_5/A_3$ is 0.55 at an altitude of 23,000 feet. The same trends are evident although the propane ramjet has a slight advantage at the low and medium fuel-air ratios. Above the stoichiometric fuel-air ratio (0.068 for JP-4 and 0.064 for propane) the performance is almost identical.

7. JP-4 RAMJET ($C_{DB}$ = 4.0 and $\eta_c$ = 0.90)

Figure 13 presents the results for a JP-4 ramjet with a burner drag coefficient of 4.0 and a combustion efficiency of 0.90. Figure 13 is directly comparable to Figure 12.

Figures 14 and 15 show the effects of additive drag with $A_C/A_3$ = 0.1976, which was chosen for the design case of $M_0$ = 0.95 and $C_F$ = 0.5.

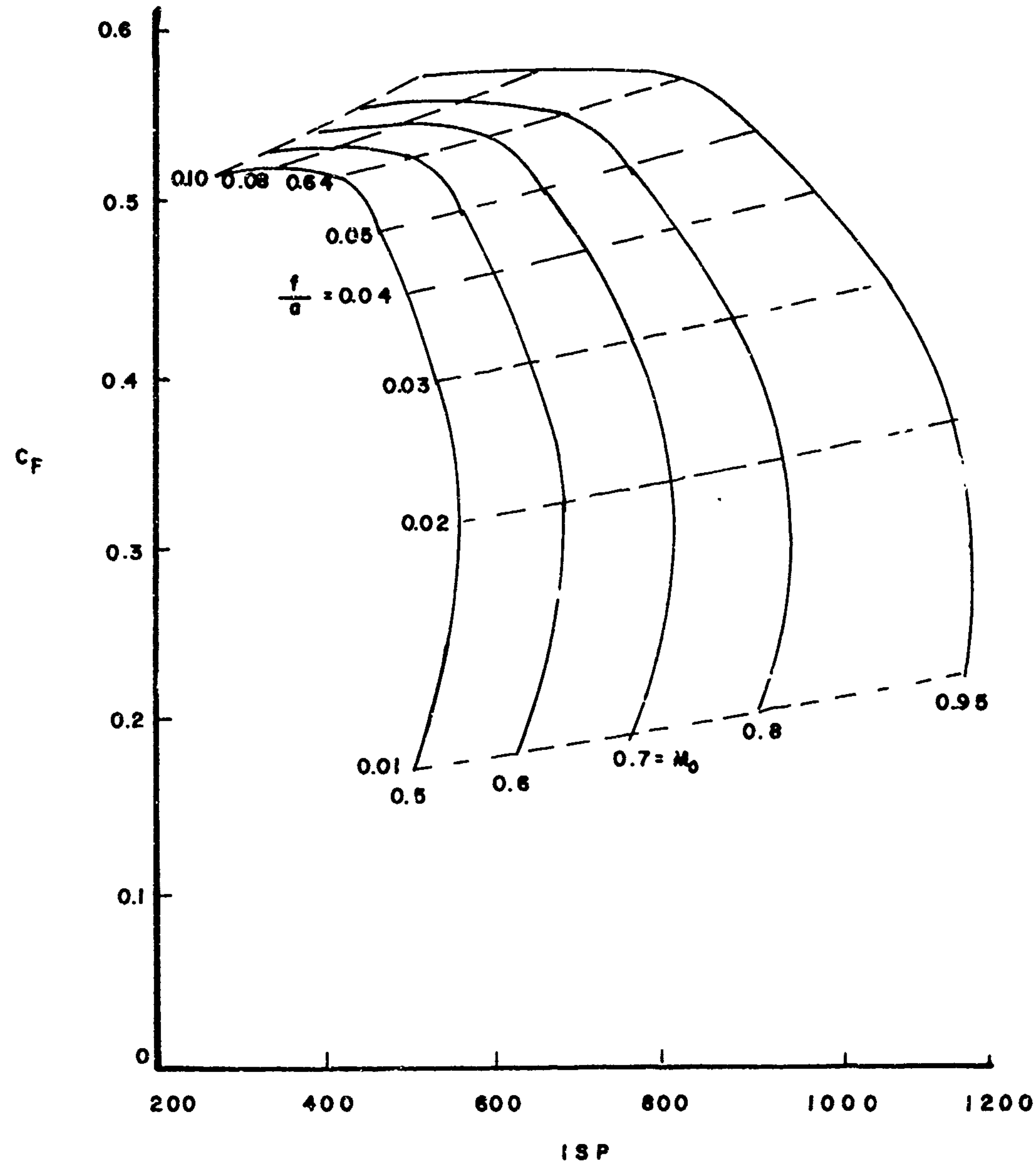


Figure 11. Propane-Fueled Ramjet Performance With $C_{D_B}$ = 4 and $\eta_c$ = 90%

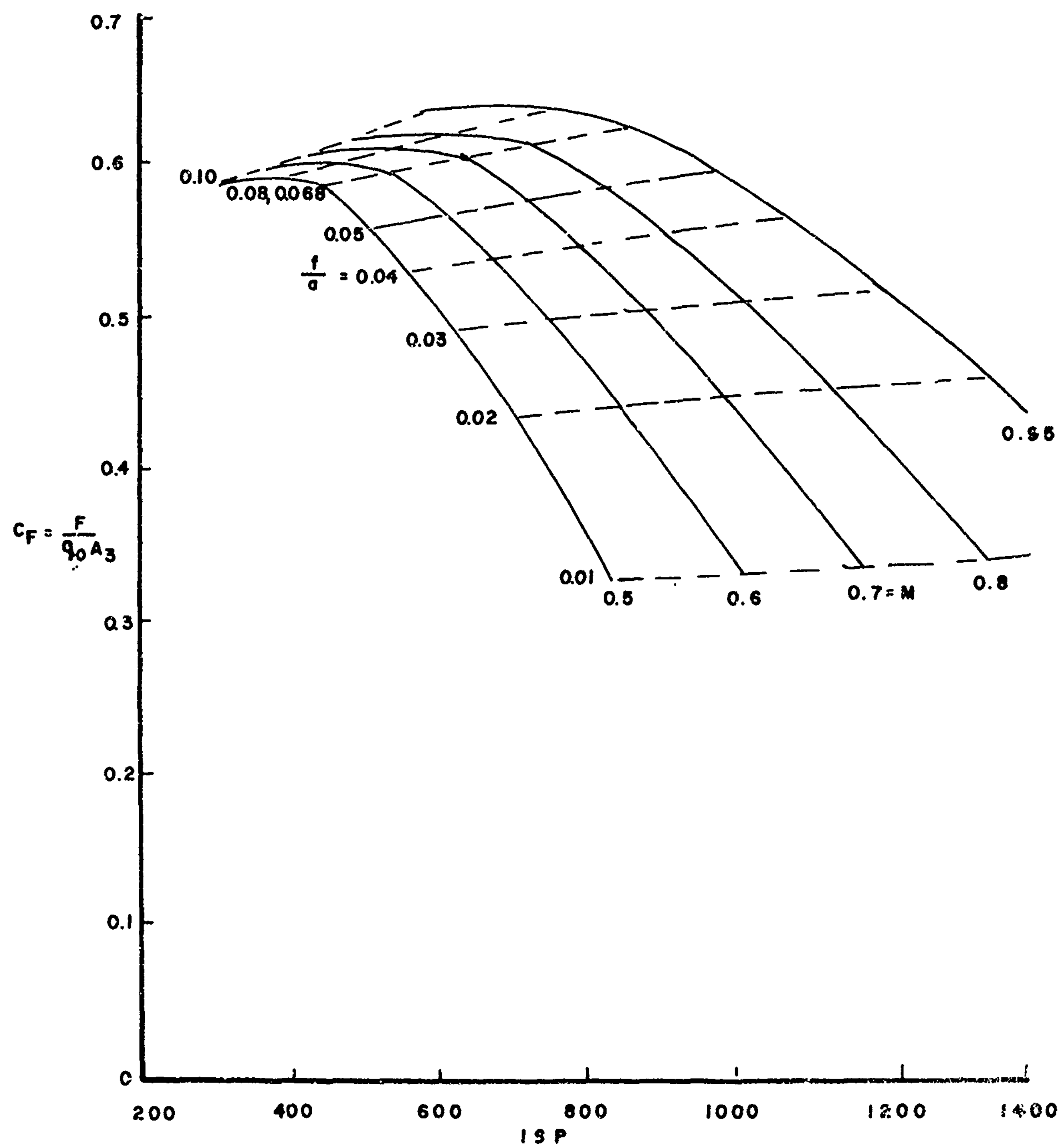


Figure 12. Ideal JP-4 Fueled Ramjet Performance

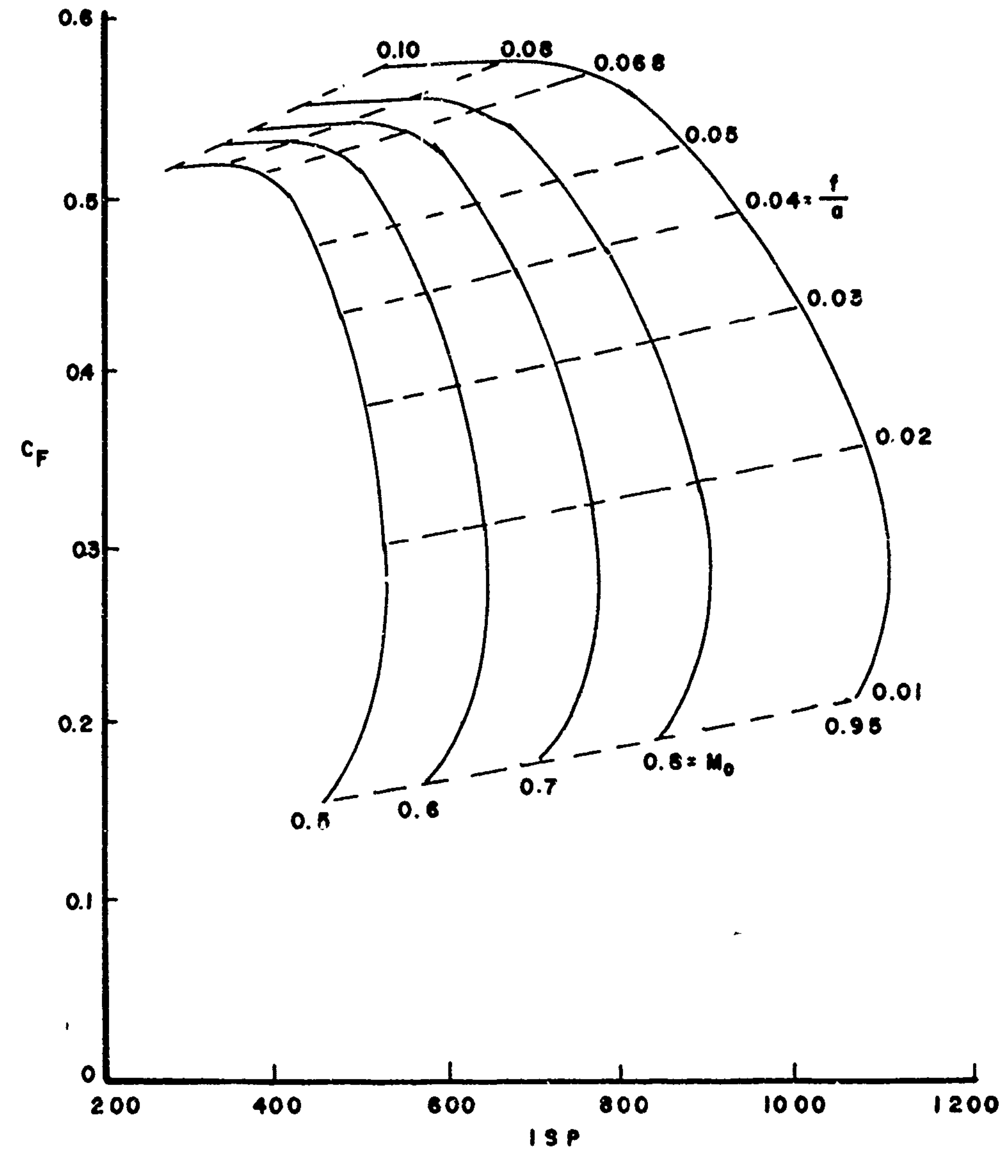


Figure 13. JP-4 Fueled Ramjet Performance With $C_{D_B}$ = 4 and $\eta_c$ = 90%

Design Point: $M_0 = 0.95$, $C_F = 0.5$, $Ac/A_3 = 0.1976$

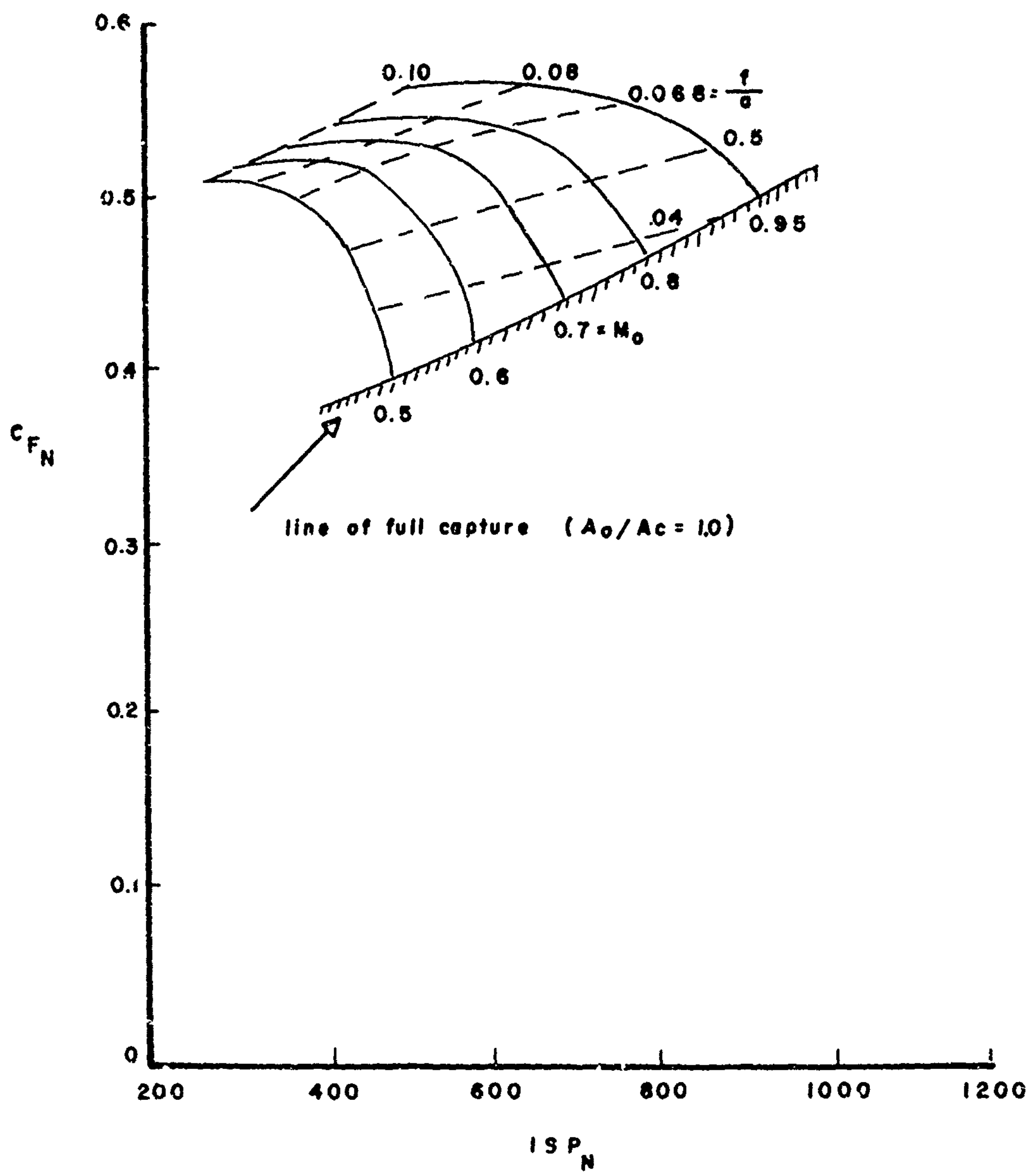


Figure 14. JP-4 Fueled Ramjet Performance With Additive Drag, $C_{D_B} = 4$, and $\eta_c = 90\%$

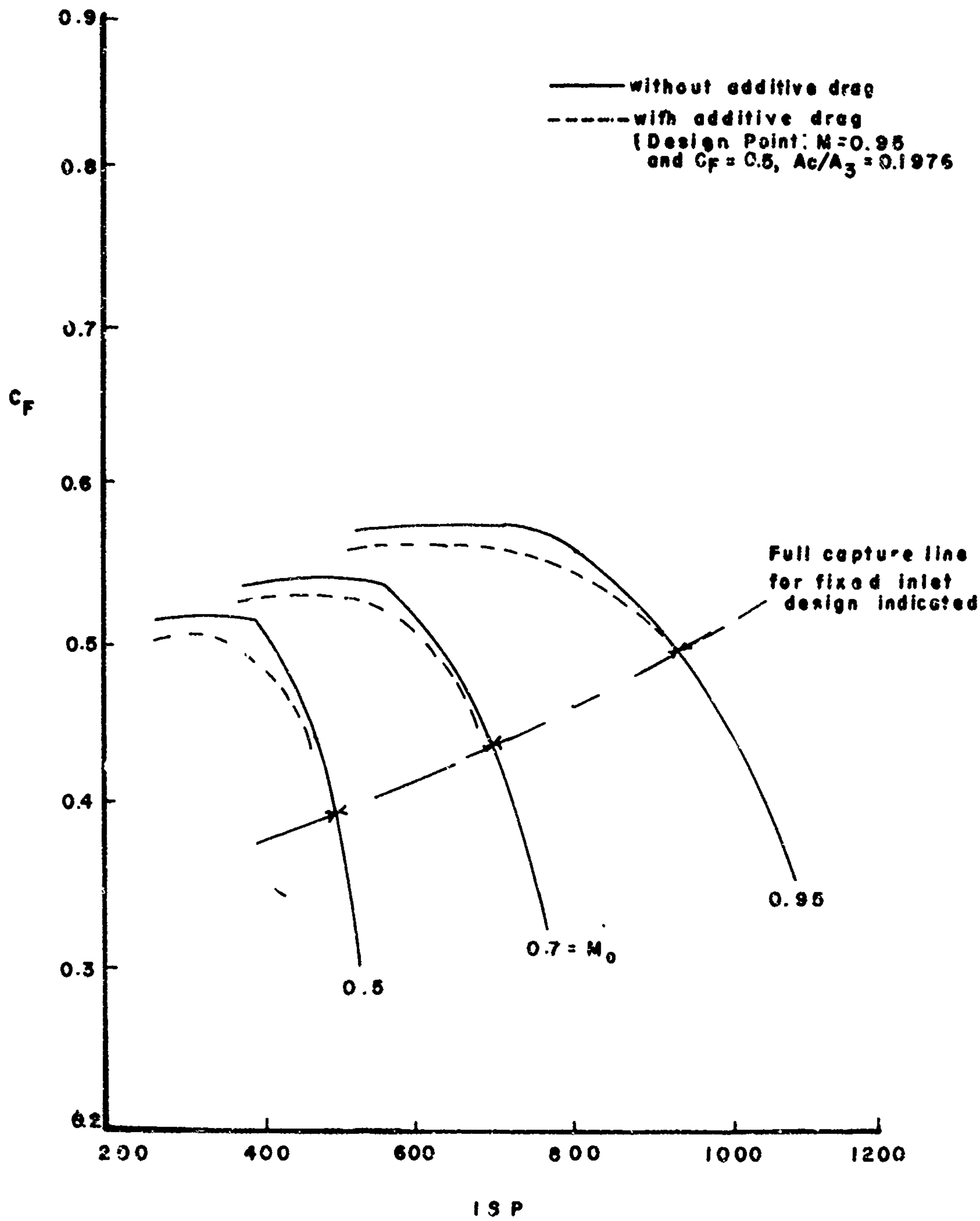


Figure 15. Effects of Additive Drag on JP-4 Fueled Ramjet Performance With $C_{D_B}$ = 4 and $\eta_c$ = 90%

# SECTION V

# COMPARISONS

The ramjet and ejector ramjet performance parametrics shown herein can be used for several comparison purposes only. The results are valid for the assumptions made. In general, an application requires that an engine operate over a wide envelope with fixed geometry, which necessitates considering additive drag. In addition, the external drag of the engine nacelle must be included, as well as any vehicle/engine interference drag. Without these specific effects, the following general comparisons can be reached.

Figure 16 compares the parametric performance of the ideal engines at Mach 0.7. The lowest point on each line is for f/a = 0.02 and the highest point is for f/a = 0.1. As the fuel/air ratio increases, the thrust increases at a sacrifice in specific impulse. At the very low fuel/air ratios the performance is nearly identical. As the fuel/air ratio increases, the advantages of the ejector ramjet become apparent. The "X" mark on each line indicates a stoichiometric fuel/air ratio. Thrust levels below this mark indicate lean engine operation, and those above this mark indicate fuel rich operation.

The propane ramjet and the propane ejector ramjet can be compared in many ways. As noticed on the ramjet curves, the thrust maximizes at about the stoichiometric fuel/air ratios; richer mixtures are of no advantage to the ramjet. Comparing the ideal engines at this stoichiometric fuel/air ratio indicates that the ideal ejector ramjet has a thrust advantage of 18% and a specific impulse advantage of 11%. The ejector ramjet can increase thrust at a sacrifice in impulse by operating fuel rich; this is no advantage to the ramjet.

Let us compare the ejector ramjet operating at a f/a = 0.1 and the ramjet operating at stoichiometric. For this case, the ejector ramjet has a thrust advantage of 37% but a specific impulse that is only 76% of that possible with the ramjet. Figure 17 shows the same comparisons at Mach 0.95. The same comparisons can be made from Figure 18 for $C_{DB}$ = 4 and $\eta_C$ = 90%. With both engines operating stoichiometrically, the ejector ramjet has a 17% thrust advantage and a 10% specific impulse advantage, slightly lower than for the ideal case. With the ejector ramjet operating at f/a = 0.1 and the ramjet at stoichiometric, the ejector ramjet has a 35% thrust advantage but again at 76% of the ramjets' specific impulse.

If the ejector ramjet has the drag predicted from References 4, 5, and 6, and the ramjet has a $C_{DB}$ = 4 and $\eta_C$ = 0.9, we obtain the following results. With both engines operating stoichiometrically, the ejector ramjet has an 8% thrust advantage and a 5% specific impulse advantage over the ramjet. With the ejector ramjet operating at f/a = 0.1, its thrust advantage over the ramjet is 21% but its specific impulse is only 65% that of the ramjet. Similar comparisons can be made at Mach 0.95 and 23,000 feet from Figure 19; it must be pointed out, however, that this comparison is made at a maximum thrust level and at a very low specific impulse level, which gives the maximum potential advantage to the ejector ramjet. For a cruise application a lean fuel/air ratio would likely be chosen to maximize specific impulse; at a condition of say f/a = 0.3, the advantage of the ejector ramjet is considerably reduced or even eliminated. For instance, at f/a = 0.3, the ramjet would produce 16% more thrust at 10% higher specific impulse. One parameter which

is important to the effectiveness of the ejector ramjet is the ratio of the primary to the inlet air stream thrust. As this parameter increases, the ejector ramjet becomes more effective in its pumping action. Figure 20 is a plot of this stream thrust ratio versus fuel/air ratio for various flight mach numbers. As can be seen, this parameter increases with increasing fuel/air ratio; therefore, the pumping action of the ejector ramjet will be greater at the higher fuel/air ratios. This effectively increases the amount of air flowing through the engine, thus giving more thrust than is possible with the conventional ramjet at the higher fuel/air ratios.

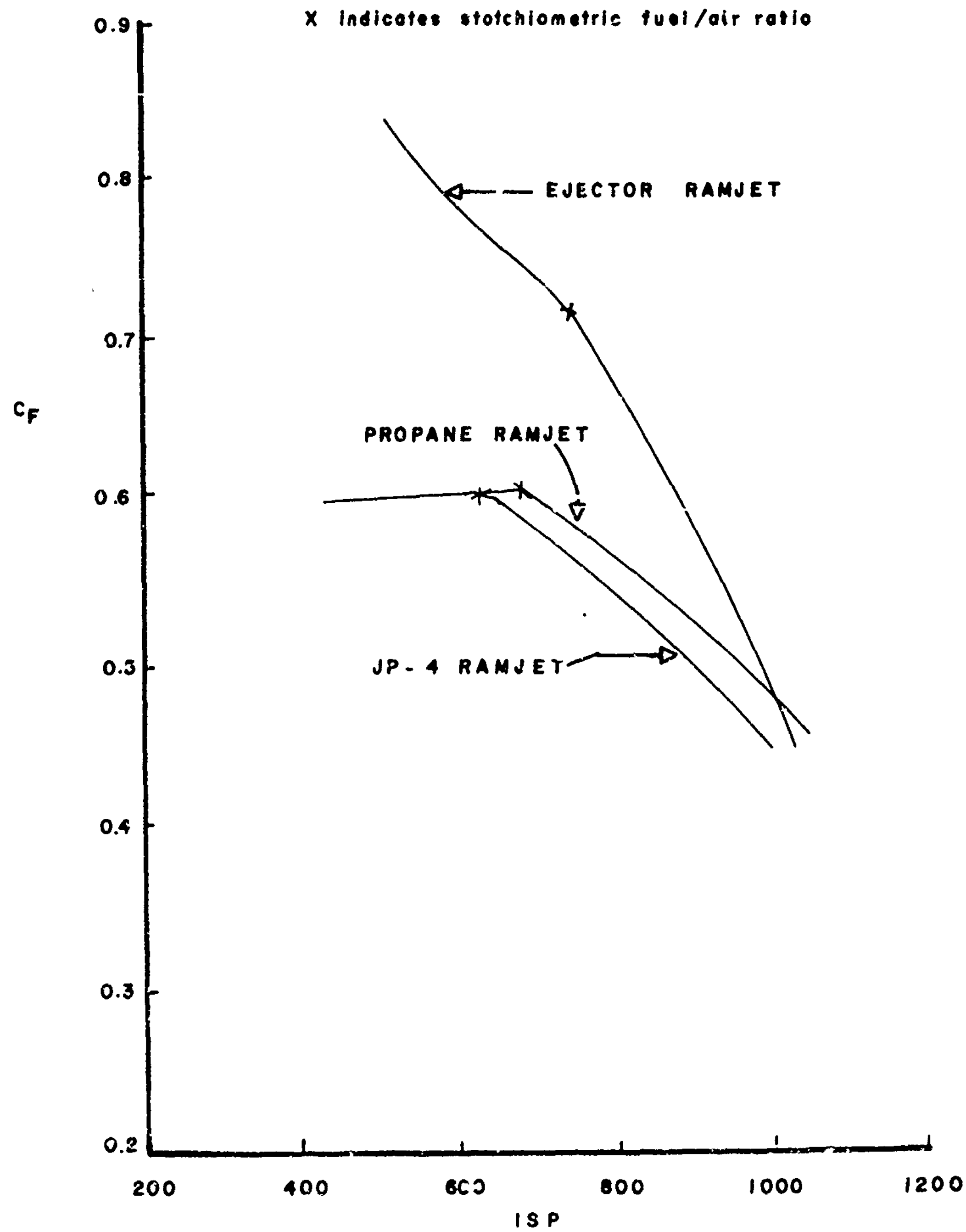


Figure 16. Comparison of the Ideal Engines at $M_0$ = 0.7

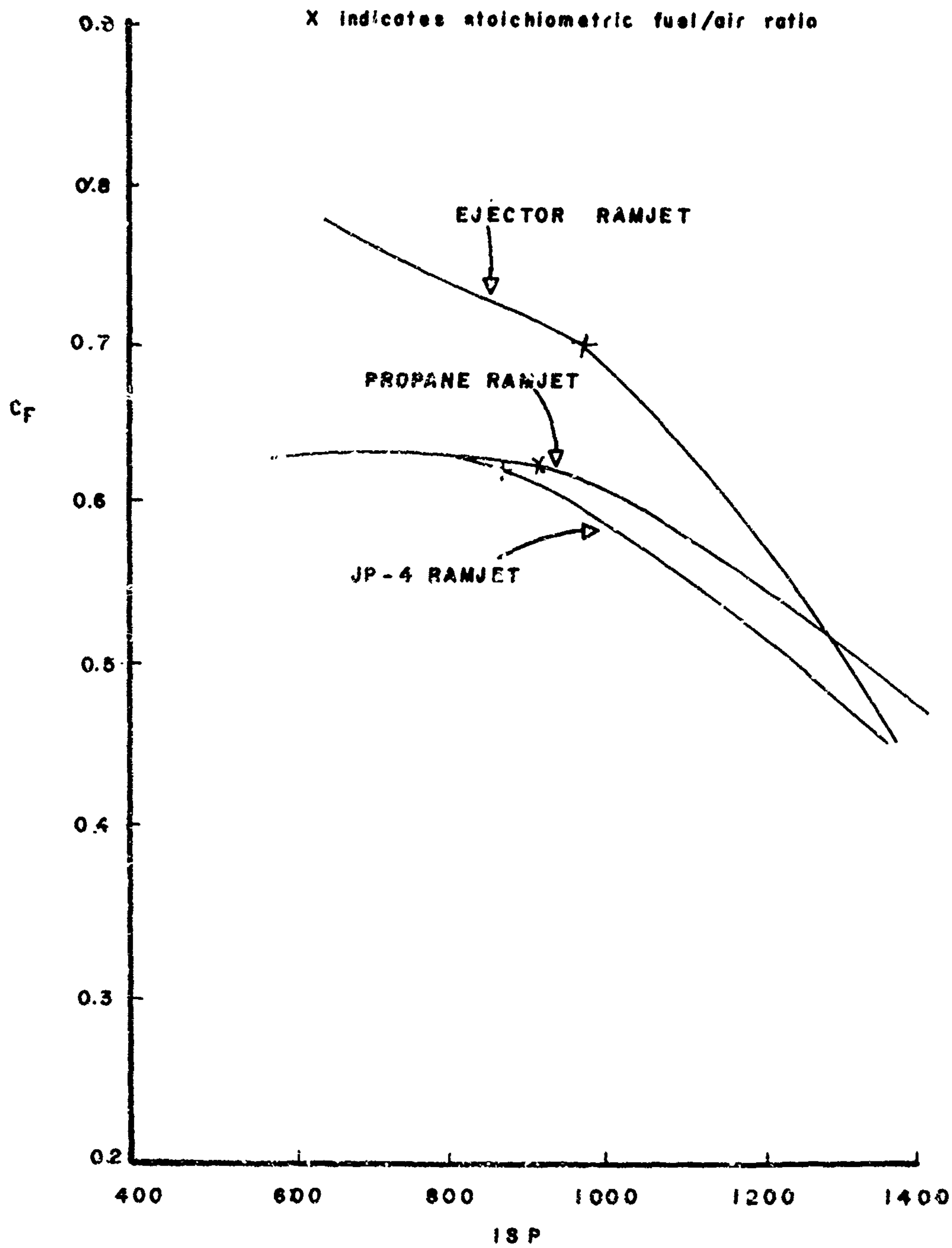


Figure 17. Comparison of the Ideal Engines at $M_0$ = 0.95

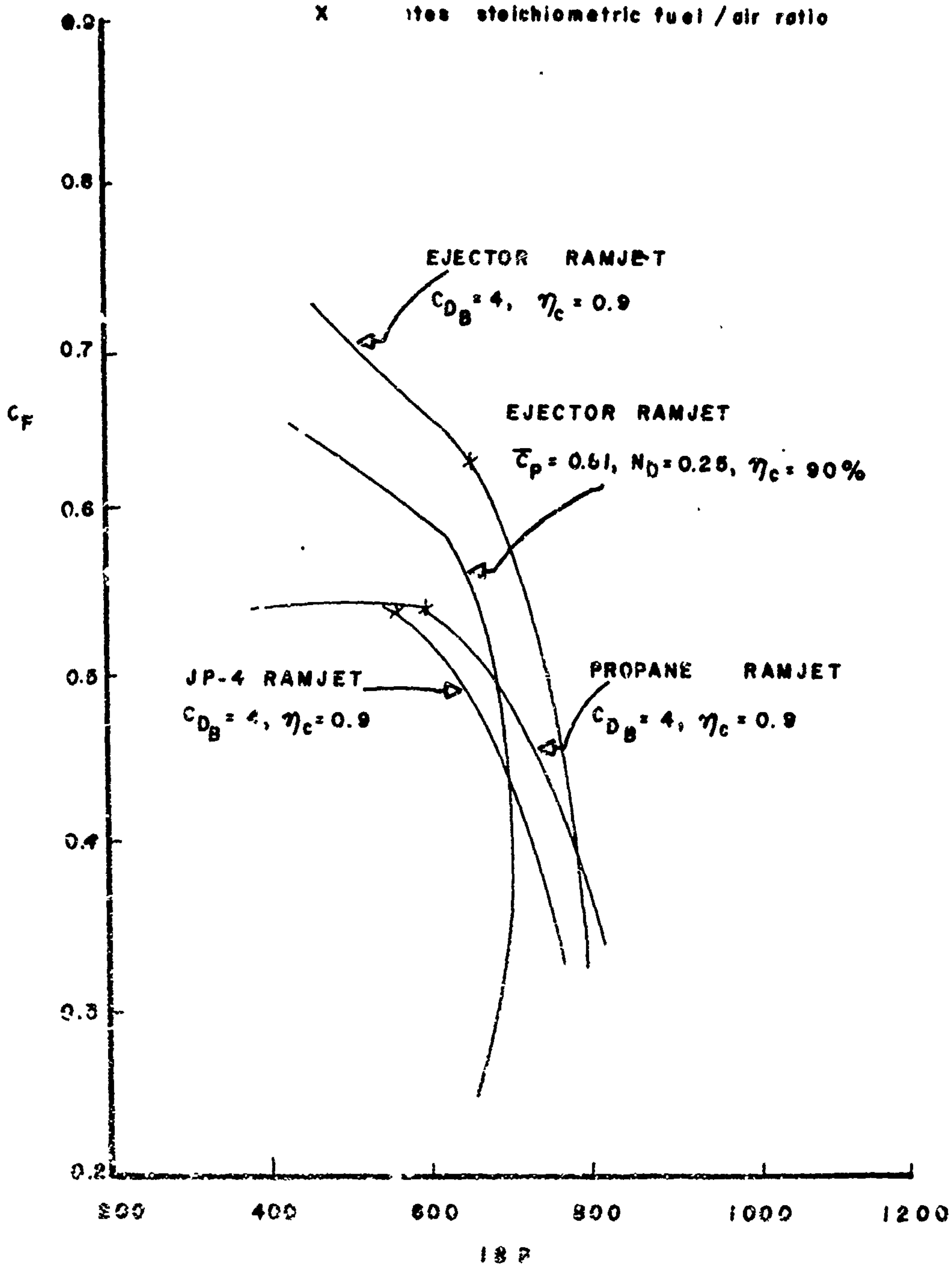


Figure 18. Comparison of the Engines With Efficiencies at $M_0 = 0.7$

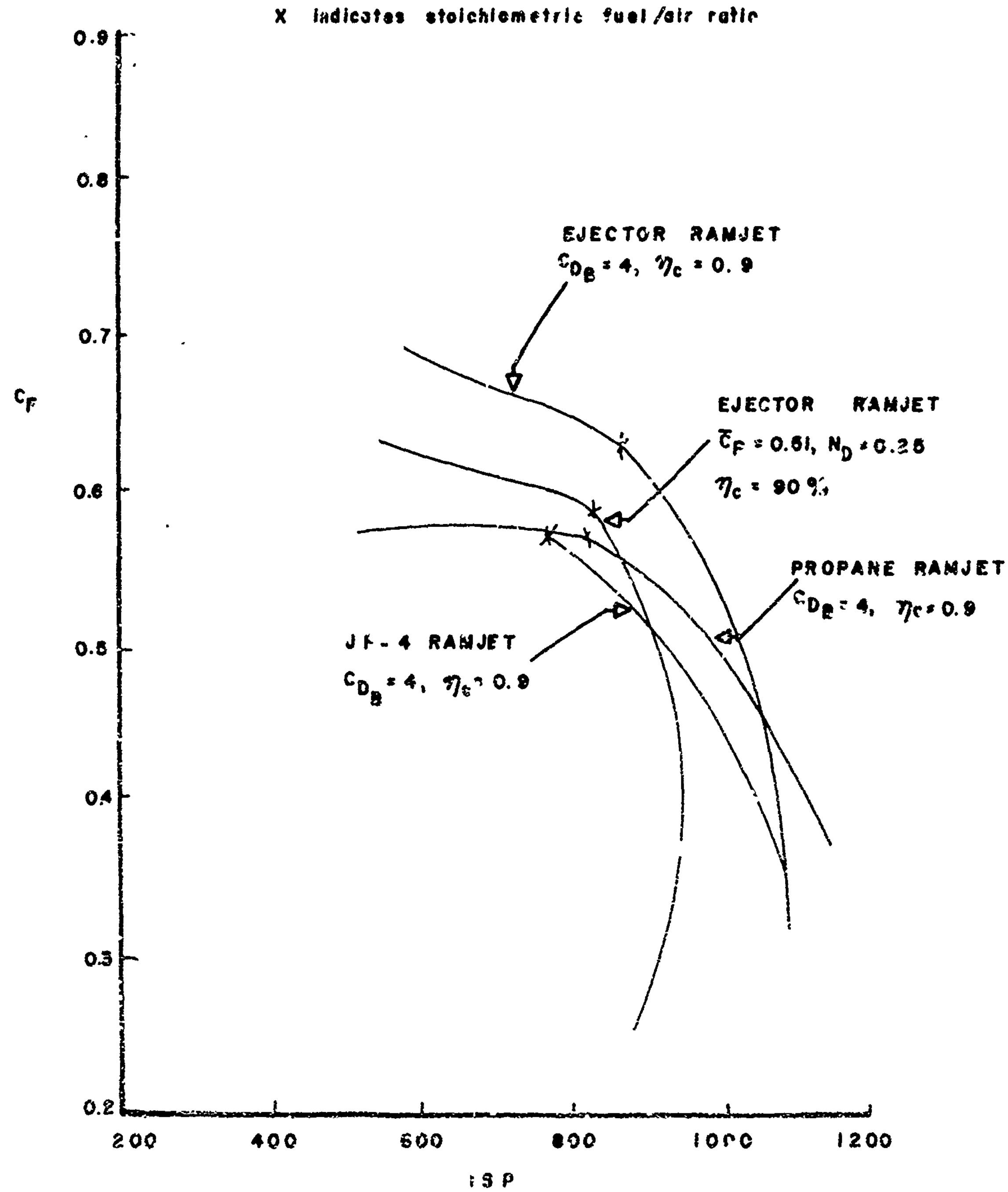


Figure 19. Comparison of the Engines With Efficiencies at $M_0$ = 0.95

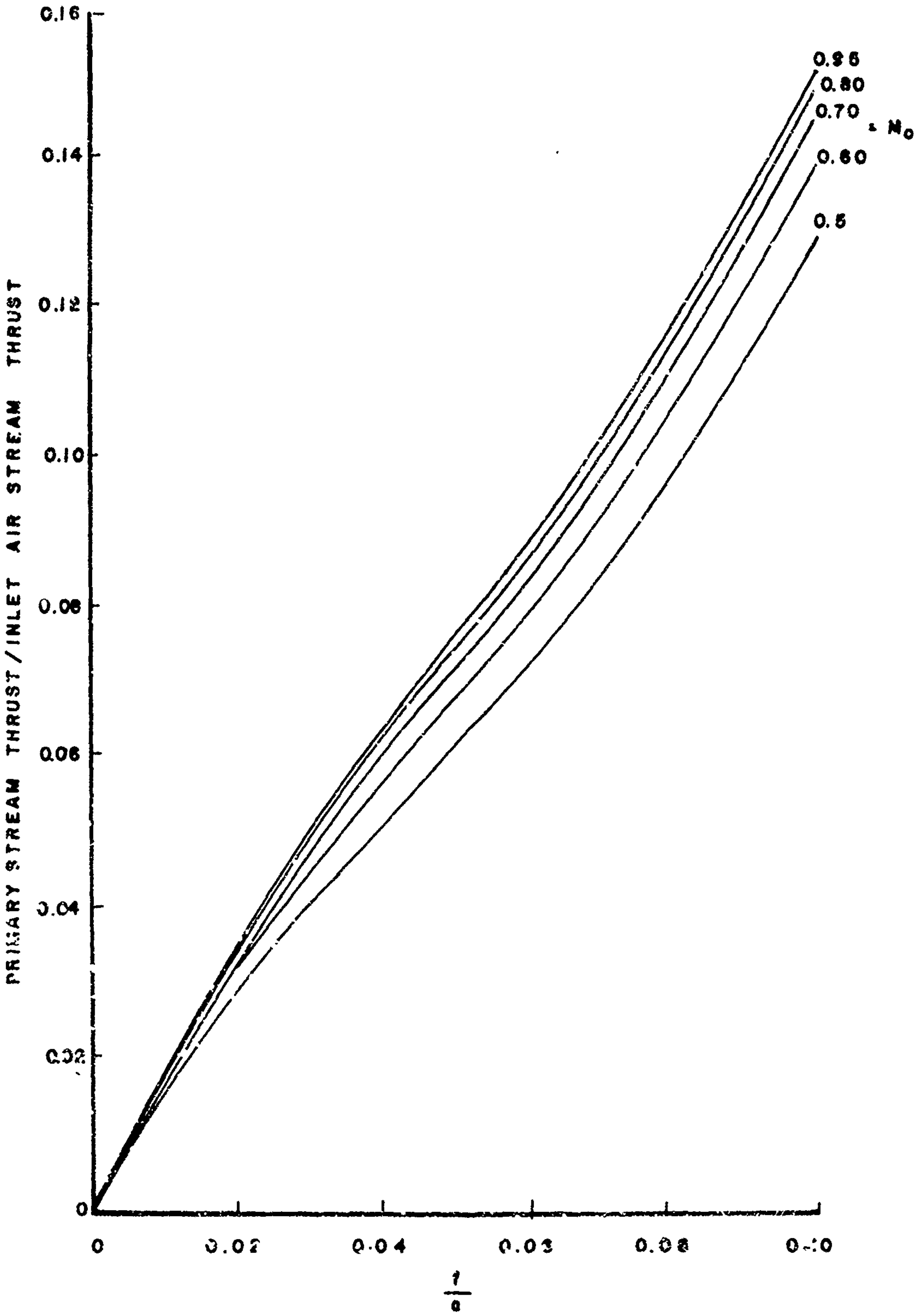


Figure 20. Ejector Ramjet Stream Thrust Ratio

# SECTION VI

# CONCLUSIONS

The potential performance of the ejector ramjet and the conventional ramjet have been determined. At high fuel/air ratios, the ejector ramjet has a thrust advantage over the conventional ramjet. The relative ranking of these two engine systems can change drastically, however, depending on the internal flow losses and combustion efficiency assumed in the analysis. In addition, the relative advantage changes greatly with the fuel/air ratio considered. The assumptions of $C_{D_B} = 4.0$ and $\eta_c = 0.90$ for the ramjet are considered as state-of-the-art values for JP-fueled ramjets. The ejector ramjet losses assumed from References 3, 4, and 5 are considered representative, although data from a real engine of this type is lacking. Predictions of internal drag in References 3, 4, and 5 are based on experimental data. Comparing these cases shows that the ejector ramjet has an advantage at the high fuel/air ratios and the conventional ramjet has an advantage at the low fuel/air ratios. The reason for this difference is that with large fuel/air ratios the ejector pumping action is greater and the cycle pressure is increased, while at the lower fuel/air ratios the ejector pumping action is less. This is directly related to the momentum ratio of the ejector to the inlet air stream which increases as the fuel/air ratio increases.

The data contained in this section is parametric, with no fixed inlet size. A real engine with a known capture area will have an actual thrust lower than that estimated herein when additive drag and external

drag are included. This was illustrated in Section IV for one particular design point. This thrust decrement should affect each engine similarly, however, and should not change the relative ranking derived from this comparison.

# APPENDIX I

## ENGINE PERFORMANCE COMPUTER PROGRAM INPUT AND OUTPUT PROCEDURES

For ease of operation, the data read into the program has been divided into four sets: (1) the fuel data set, which contains the tables of gamma, molecular weight, and temperature rise for the combustion products as a function of initial temperature and fuel-air ratio; (2) the engine geometry and the efficiency parameters, initial values of which are built into the program; since this set of data is entered in Namelist form, only those parameters having values different from the initial values need be entered; (3) flight parameters at which the engine is to operate, including the Mach numbers, altitudes, and fuel-air ratios for which engine performance is to be calculated; (4) the job title and the job code. The order of the first three data sets in the data deck is not fixed, but the fourth set must appear last.

Each data set is identified by a key word which alerts the program that the following data belongs to a particular data set. The key words corresponding to the above four data sets are: FUEL, GEOMETRY, RANGE, and PROBLEM. Each key word must start in column one. Tables I through IV display the form of all the input data cards.

Table I shows the format for the fuel card set. Card 1 contains the word, FUEL, starting in column one. Nothing else appears on this card. Card 2 contains two numerical values: the number of fuel-air ratios to be entered later in columns 1-10, and the number of initial

air total temperatures in columns 11-20. Card 3 gives the list of fuel-air ratios, starting in column 11, with six numbers per card; up to three cards may be required. The first ten and the last ten columns of these cards are reserved for identification data. (This identification data is not used by the computer.) The other lists of data in this set are entered on the same format. Each list begins on a new card.

Table II shows the variables that are entered on a Namelist card. A description of this type of data entry is given in the Fortran Extended manual.

Table III shows the format for the flight parameters. Card 1 contains the word, RANGE, starting in column one. The second card contains the number of Mach numbers, number of altitudes, and the number of fuel-air ratios. Ten spaces are allotted per number, starting in column one. The third card contains the list of Mach numbers, where each number is allotted ten spaces. The other two lists are similar, except that the fuel-air ratio list may require more than one card to complete the list. Figure 21 shows a typical data deck.

The printed output from the program gives the cycle performance and many engine parameters. Line 1 shows the problem title and the altitude. Line 2 shows the capture area in square feet, the conventional thrust in pounds, the corresponding thrust coefficient, specific impulse, specific fuel consumption, fuel-air ratio, and the flight Mach number. Line 4 shows the values of thrust in pounds, thrust coefficient, specific impulse, and specific fuel consumption, which have been corrected for

additive drag. Line 5 presents the engine stations and serves as a title for the data immediately below. Column titled E presents data for the exit of the ejector, which is used only for ejector ramjet problems. Line 6 gives the Mach number at each station. Line 7 presents some of the important values of gamma that were used. Line 8 shows the flow area in square feet at each engine station. Line 9 shows the pressure in atmospheres at each engine station. Line 10 shows the total pressure in atmospheres at some of the engine stations. Line 11 gives the total temperature in °R at some of the important engine stations. Line 12 shows the stream thrust in pounds force for some stations. Line 13 shows the molecular weight at two stations. Finally, the last line shows a convergence parameter titled cycle, the free stream pressure in $lbs/ft^2$ the pressure at the engine exit in $lbs/ft^2$, the air flow rate in lbs/sec, and the fuel flow rate in lbs/sec. A sample output is shown in Figure 22.

TABLE I - FUEL CARDS

| Card Order | Contents | Format |
|---|---|---|
| 1 | FUEL | A10 |
| 2 | Number of fuel-air ratios (max value - 18)<br>Number of initial air temps (max value - 12) | 2I10 |
| 3 | List of fuel-air ratios | 10X,6E10.0 |
| 4 | List of initial air temperatures | 10X,6E10.0 |
| 5 | List of temperature rise data corresponding to the fuel-air ratios and the initial air temperatures. | 10X,6E10.0 |
| 6 | List of molecular weight data corresponding to the fuel-air ratios and the initial air temperatures. | 10X,6E10.0 |
| 7 | List of gammas corresponding to the fuel-air ratios and the initial air temperatures. | 10X,6E10.0 |

## TABLE II - VARIABLES IN GEØM NAMELIST

The key word GEØMETRY precedes the namelist data. This word is read in on a A10 format.

| Variable | Type | Value Before Read | Definition & Comments |
|---|---|---|---|
| A1 | R | 1.23 | Area of station 1 in sq. ft. |
| ASTAR | R | 0.00753 | Area of ejector throat, sq. ft. |
| AE | R | 0.030121 | Area of the ejector exit, sq. ft. |
| A2 | R | 1.2601 | Area of station 2 in sq. ft. |
| A3 | R | 5.2414 | Area of station 3 is sq. ft. |
| A5 | R | 2.8852 | Area of station 5 in sq. ft. |
| DUMPLØS | L | FALSE | Calculate diffuser & dump losses if true |
| ETAF2 | L | FALSE | Use a fraction, ETAMIX, of the ideal momentum at station 2 if true |
| ETAFE | L | FALSE | Use a fraction, ETAMIX, of the ideal ejector momentum if true |
| ETAMIX | R | 0.0 | Mixing efficiency |
| TTF | R | 1300.0 | Total temperature of ejector flow in °R |
| A2P | R | 2.52 | Area of station 2' in sq. ft. |
| ND | R | 0.25 | Dump loss parameter |
| CPR | R | 0.51 | Diffuser performance parameter |
| $C_{DB}$ | R | 0.0 | Burner drag coefficient |
| $\eta_c$ | R | 1.0 | Combustion efficiency |

TABLE III - FLIGHT PARAMETERS

| Card Order | Contents | Format |
|---|---|---|
| 1 | RANGE | A10 |
| 2 | Number of Mach numbers (Max - 8)<br>Number of altitudes (Max - 4)<br>Number of fuel-air ratios (Max - 20) | 3I10 |
| 3 | List of Mach number | 8E10.0 |
| 4 | List of altitudes | 4E10.0 |
| 5 | List of fuel-air ratios | 8E10.0 |

TABLE IV - ENGINE IDENTIFICATION DATA

| Card Order | Contents | Format |
|---|---|---|
| 1 | PRØBLEM | A10 |
| 2 | Job title and job code<br>(For an ejector ramjet the job code is any integer less than or equal to 0. For a ramjet use any integer greater than 0.)<br>(The job title can be any comment the user wishes to make) | 12A6,I8 |

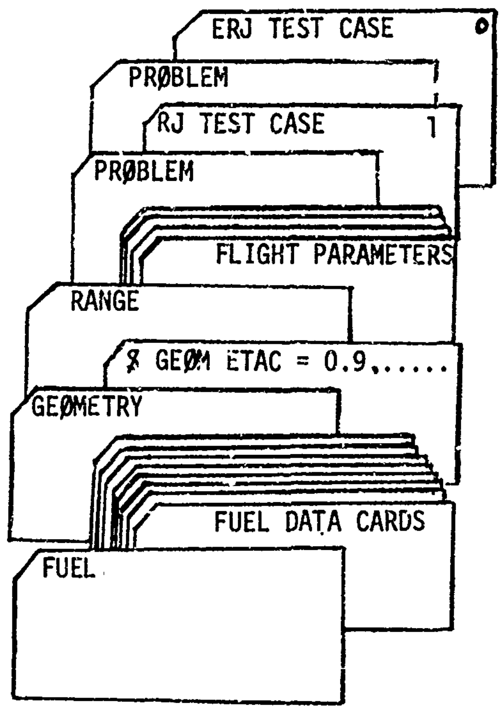


Figure 21. Typical Data Deck

MOMENTUM COMPRESSION RJ CHECKOUT. ALT = 23000.0

| AO | THRUST | CF | ISP | SFC | FAR | AMO |
|---|---|---|---|---|---|---|
| .9401E+00 | .3537E+03 | .4499E+00 | 498.9458 | 7.2152 | .0400 | .50 |
| ADDITIVE DRAG | .3411E+03 | .4339E+00 | 481.1822 | 7.4816 | | |

| STATION | 0 | 1 | 2 | 3 | 4 | 5 | E |
|---|---|---|---|---|---|---|---|
| Mach | .5000 | .3558 | .3909 | .0893 | .2280 | .4506 | 2.4316 |
| Gam | | | 1.3837 | | 1.2659 | | 1 0689 |
| Area-sq.ft. | .9401E+00 | .1230E+01 | .1260E+01 | .5241E+01 | | .2885E+01 | .3012E-01 |
| Pres-ATM | .4051E+00 | .4402E+00 | .4395E+00 | .4691E+00 | .4565E+00 | .4051E+00 | .1518E+00 |
| TOTP-ATM | .4805E+00 | | .4878E+00 | .4717E+00 | .4599E+00 | | .2694E+01 |
| TOTT-°R | .459E+03 | | .5382E+03 | | .2834E+04 | | |
| Stream-LBF | | 1349.0719 | 1419.9204 | | | 3109.1281 | 70.8485 |
| Mol Wt | | | 29.352 | | 28.514 | | |

C.CLE = -.98159E-06 PO = .857244E+03 $P_5$ = .357245E+03 WA = .1772E+02 WF = .7090E+00

Figure 22. Sample Output

# APPENDIX II

# PROGRAM LISTING

```
1H      MOMCRJ                                        CDC 6600 FTN V3.0-251A OPT=1  07/15/71

          PROGRAM MOMCRJ (INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT)
          REAL ND
          EXTERNAL CYCLE, BUMAG, AINLET, BINLET
          LOGICAL DUMPLOS, RJ, TRAP, ETAF2, ETAFE
          DIMENSION AAMO(4), AALT(4), AFAR(20), TITLE(12)
          COMMON /CYCL/ A5, F5, RJ, TT4, GAM4, WTM4, TT0, ETAC
          COMMON /BUMA/ AM3, CDB, T4P
          COMMON /AINLT/ A1, AC, AE, ASTAR, AM0, AM1, AM3CK, DUMPLOS,
         1 ETAMIX, ETAF2, ETAFE, FAR, GAMT, INKT, P0, PT0, TC, TTF
          COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,ND
          NAMELIST/GEOM/ DUMPLOS, ETAF2, ETAFE, ETAMIX, TTF, A1, ASTAR,
         1 AE, A2, A3, A5, A2P,CPR, ND, CDB, ETAC
          DATA FUE/4HFUEL/, GEO/8HGEOMETRY/, RANG/5HRANGE/,PROB/7HPROBLEM/
          ETAF2 = .FALSE.
          ETAFE = .FALSE.
          DUMPLOS = .FALSE.
          TTF = 1300.0
          A2P = 2.52
          ETAMIX = 1.0
          CPR = 0.51
          ND = 0.25
          CDB = 0.0
          ETAC = 1.0
          A1 = 1.23
          ASTAR = 0.00753
          AE = 0.030121
          A2 = 1.2601
          A3 = 5.2414
          A5 = 2.8852
          AMOLA = 1.0/28.966
    1     READ (5,2) WORD
    2     FORMAT (A10)
          WRITE (6,3) WORD
    3     FORMAT (1H A10)
          IF (WORD .EQ. FUE) GO TO 10
          IF (WORD .EQ. GEO) GO TO 20
          IF (WORD .EQ. RANG)  GO TO 111
          IF (WORD .EQ. PROB)  GO TO 701
          WRITE (6,25)
   25     FORMAT (10H STOP PROB)
          GO TO 1000
   10     CALL FUELDAT(0.0, 0.0, 0.0, 0.0, 0.)
          GO TO 1
   20     READ (5,GEOM)
          GO TO 1
  111     READ (5,1110) NUMAMO, NUMALT, NUMFAR
 1110     FORMAT (3I10)
          READ (5,700) (AAMO(I), I=1,NUMAMO)
          READ (5,700) (AALT(I), I=1,NUMALT)
          READ (5,700) (AFAR(I), I=1,NUMFAR)
          GO TO 1
  700     FORMAT (8E10.0)
  701     READ (5,112) (TITLE(I), I=1,12), ICODE
  112     FORMAT (12A6, I8)
          IF (EOF(5)) 1000, 1002
```

```
1002  CONTINUE
      RJ = .FALSE.
      IF (ICODE .GT. 0)  RJ = .TRUE.
      DO 705  J1 = 1, NUMALT
      ALT = AALT(J1)
      CALL ATMOS (ALT, T0, DAPSL, RHO, TATSL, PAPSL, C, VIS, 1)
      P0 = PAPSL*144.0*14.696
      DO 705  J2=1,NUMAM0
      AM0 = AAM0(J2)
      TT0 = T0*TR(1.4, AM0)
      WRITE (6,13)
13    FORMAT (1H0 13(10H*   *   *   ))
      PT0 = P0*(1.0 + 0.2*(AM0**2))**3.5
      IF (RJ)  GO TO 15
      TTHRAT = TTF*0.83/1.8
      CALL PROPAN (TTHRAT, CPF, HFAKF)
      GAMT = CPF/(CPF - 1.987)
      TC= TTF/1.8
      CALL PROPAN (TC, CPC, HTF)
      TAIR = T0/1.8
      CALL AIRTHP (TAIR, CPA, HAIR)
      HTA = HAIR + (28.966*(C*AM0)**2)/(2.0*32.2*778.16*1.8)
15    DO  705   J3=1,NUMFAR
      FAR = AFAR(J3)
      CALL FUELINT (TT0, FAR, DT, WTM4. GAM4)
      TT4 = TT0 + ETAC*DT
      IF (RJ) GO TO 498
      AMOLF = FAR/44.0
      TK2 = 350.0
      HT2 = (AMOLA*HTA + AMOLF*HTF)/(AMOLA + AMOLF)
      DO  201   I=1,3
      CALL PROPAN (TK2, CPF, H)
      CALL AIRTHR (TK2, CPA, H1)
      CP = (AMOLA*CPA + AMOLF*CPF)/(AMOLA + AMOLF)
      TK2CK = HT2/CP + 300.0
      TCHEK = TK2CK - TK2
201   TK2 = TK2CK
      TT2 = TK2*1.8
      AWT = (1.0 + FAR)/(AMOLA + AMOLF)
      GAM2 = CP/(CP - 1.987)
498   ACLOW = 0.1*A3
      IF (.NOT. RJ)  GO TO 489
      A1 = A2
      AWT = 28.966
      TT2 = TT0
      GAM2 = 1.4
489   ACHIGH = A1
      X5 = X(GAM4, 1.0)
      X4 = X5*A5/A3
      AM4 = XM(X4, GAM4)
      Z4=Z(GAM4, AM4)
      Y4 = Y(GAM4, AM4)
      Y4P = Y4*SQRT(WTM4*TT2/(AWT*TT4*GAM2))
      IF (RJ) Y4P = Y4P/(1.0+FAR)
      CALL SOLNEW (BUMAC, 0.0, AM4, TRAP, Y1)
```

```
      AM3 = Y1
      ACT = AT*X(1.4,AM3)/X(1.4,AM0)
      IF (RJ) GO TO36
      INKT = 0
      ACH = A1
      ACL = A1/2.0
      CALL SOLNEW (BINLET, ACH, ACL, TRAP, Y1)
      IF (.NOT. TRAP) GO TO 460
      WRITE (6,34)
34    FORMAT (20H0BINLET - TRAP= TRUE)
      GO TO 240
460   ACMAX =AC
      ACL = 0.75*ACT
      IF (ACL .GT. ACMAX) ACL = 0.75*ACMAX
      INKT = 5
      CALL SOLNEW(AINLET, ACMAX, ACL, TRAP, Y1)
      IF (.NOT. TRAP)  GO TO 17
      WRITE (6,35)
35    FORMAT (13H TRAP IS TRUE)
      GO TO 240
17    IF (INKT .GT. 1)  GO TO 37
      IF ( AM3CK .GE. AM3) GO TO 37
      ACHIGH = ACMAX
      GO TO 499
36    PT3 = PT0
37    Z3 = Z(GAM2, AM3)
      PT4=PT3*(Z3/Z4-0.5*COB*GAM2*AM3**2/(Z4*PR(GAM2,AM3)))
      P5 = PT4/PR(GAM4,1.0)
      IF (.NOT. RJ) ACT = AC
      IF (P5 .LT. P0)  GO TO 497
      CALL CYCLE (ACT)
      GO TO 240
497   ACHIGH = ACT
499   CALL SOLNEW (CYCLE, ACLOW, ACHIGH, TRAP, YNEW)
      IF (.NOT. TRAP) GO TO 240
      WRITE (6,500)
500   FORMAT ( 1H0, 5X, 11HTRAP = TRUE)
240   Z0 = Z(1.4, AM0)
      F0 = PT0*AC*Z0
      Z1 = Z(1.4,AM1)
      F1 = PT0*A1*Z1
      THRUST = F5 - F0 - P0*(A5-AC)
      THRUSTN = F5 - F1 -P0*(A5-A1)
      FISP = THRUST/WF
      FISPN = THRUSTN/WF
      SFC = 3600.0/FISP
      SFCN = 3600.0/FISPN
      DEN = 0.5*1.4*P0*A3*AM0**2
      CF = THRUST/DEN
      CFN = THRUSTN/DEN
      WRITE (6,300) (TITLE(I), I=1,12), ALT, AC, THRUST, CF, FISP,
     2  SFC, FAR, AM0, THRUSTN, CFN, FISPN, SFCN
300   FORMAT(1H0/1H012A6,15X,4HALT=,F10.1/1H 8X,2HA0,12X,6HTHRUST,
     1 11X, 2HCF, 13X, 3HISP, 12X, 3HSFC, 14X, 3HFAR, 12X, 3HAM0/
     2 1H 3E15.4,3F15.4,F15.2/14H ADDITIVE DRAG,2E15.4,3F15.4)
```

```
AM      MOMCRJ                                    CDC 6600 FTN V3.0-251A OPT=1  07/15/71

            FUN = HCYCLE (0.0)
      705   CONTINUE
            GO TO 1
     1000   STOP
            END
```

```
ION     CYCLE                                          CDC 6600 FTN V3.0-251A OPT=1   07/15/71
            FUNCTION CYCLE (ROOT)
            LOGICAL RJ, NSOL, DUMPLOS, ETAF2, ETAFE
            COMMON /CYCL/ A5, F5, RJ, TT4, GAM4, WTM4, TT0, ETAC
            COMMON /BUMA/ AM3, CDB, Y4P
            COMMON /AINLT/ A1, AC, AE, ASTAR, AM0, AM1, AM3CK, DUMPLOS,
           1 ETAMIX, ETAF2, ETAFE, FAR, GAMT, INKT, P0, PT0, T0, TTF
            COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,ND
      1     AC = ROOT
            X1 = AC*X(1.4, AM0)/A1
            AM1 = XM(X1, 1.4)
            P1 = PT0/PR(1.4,AM1)
            WA = P0*AC*AM0*SQRT((1.4*32.2*28.966)/(1545.264*T0))
            FA1 = PT0*A1*Z(1.4, AM1)
            WF = WA*FAR
            IF (.NOT. RJ) GO TO 5
            AM2 = AM1
            F2 = FA1
            GO TO 52
      5     XSTAR = X(GAMT, 1.0)
            PTP = (WF*SQRT((TTF*1545.264)/(32.2*44.0)))/(ASTAR*XSTAR)
            PTH = PTP/PR(GAMT, 1.0)
            IF(PTH.LT.P1) GO TO 10
            XE = XSTAR*ASTAR/AE
            AME = SMX (XE, GAMT)
            FE = PTP*AE*Z(GAMT, AME)
            GO TO 15
      10    AME=WF/(P1*AE*SQRT(GAMT*32.2*44./(1545.264*TTF)))
            FE = P1*AE*(1.0+GAMT*(AME**2))
            PTP = P1*PR(GAMT, AME)
      15    F2 = FA1 + FE
            IF(ETAF2)  F2= ETAMIX*F2
            IF (ETAFE)  F2 = FA1 + ETAMIX*FE
            Y2 = ((WA + WF)*SQRT(TT2*1545.264/(32.2*AWT)))/F2
      50    AM2 = YM(Y2, GAM2)
      52    Z2 = Z(GAM2,AM2)
            X2 = X (GAM2, AM2)
            IF (RJ) GO TO 56
            IF (DUMPLOS)  GO TO 57
      56    X3 = X2*A2/A3
            PT3 = ((WA+WF)*SQRT(TT2*1545.264/(32.2*AWT)))/(A3*X3)
            IF(RJ) PT3=(WA*SQRT(TT2*1545.264/(32.2*AWT)))/(A3*X3)
            GO TO 58
      57    CALL DUMP  (Z2, X3)
      58    AM3 = XM (X3, GAM2)
            Y3 = Y (GAM2, AM3)
            Z3 = Z (GAM2, AM3)
            P3 = PT3/PR(GAM2,AM3)
            P3ATM = P3/(144.0*14.696)
      70    Y4 =Y3*SQRT(AWT*TT4/(WTM4*TT2))
            Y4 = Y4*(1.0 + GAM2*AM3**2)/(1.0+GAM2*AM3**2*(1.0-0.5*CDB))
            IF (RJ) Y4 = Y4*(1.0+FAR)
            AM4 = YM(Y4, GAM4)
            X4 = X(GAM4, AM4)
            X5 = X4*A3/A5
            AM5 = XM(X5, GAM4)
```

```
ION    CYCLE                                   CDC 6600 FTN V3.0-251A OPT=1  07/15/71
              Z4 = Z(GAM4, AM4)
              PT4 = PT3*(Z3/Z4 - 0.5*CDB*GAM2*AM3**2/(Z4*PR(GAM2,AM3)))
              P5 = PT4/PR(GAM4,AM5)
              Z5 = Z(GAM4, AM5)
              F5 = ~ 4*A5*Z5
              CY    1.0 - P5/P0
              GO TO 300
              ENTRY WCYCLE
              PT2A = F2/(A2*Z2*2116.224)
              P2 = PT2A/PR(GAM2,AM2)
              P4 = PT3/(2116.224*PR(GAM4,AM4))
              P0ATM = P0/2116.224
              P5ATM = P5/2116.224
              PT0A = PT0/2116.224
              P1 = P1/2116.224
              PT3A = PT3/2116.224
              PT4A = PT4/2116.224
              IF (RJ) GO TO 200
              PTPA = PTP/2116.224
              PEA = PTPA/PR(GAMT,AME)
     200      WRITE (6,250) AM0, AM1, AM2, AM3, AM4, AM5, AME, GAM2, GAM4,
             1 GAMT, AC, A1, A2, A3, A5, AE, P0ATM, P1, P2, P3ATM, P4, P5ATM,
             2 PEA, PT0A, PT2A, PT3A, PT4A, PTPA, TT0, TT2, TT4, FA1, F2, F5,
             3 FE, AWT, WTM4
     250      FORMAT(8H0STATION, 9X, 1H0, 15X, 1H1, 15X, 1H2, 15X, 1H3, 15X,
             1  1H4, 15X, 1H5, 15X, 1HE/ 5H MACH, F15.4, 6F16.4/ 4H GAM, 32X,
             2  F16.4, 16X, F16.4, 16X, F16.4/ 5H AREA, 2X, 4E16.4, 16X,
             3 2E16.4/ 5H PRES, 2X, 7E16.4/ 5H TOTP, 2X, F16.4, 15X, 3E16.4,
             4 16X, F16.4/ 5H TOTT, 2X, E16.3, 16X, E16.4, 16X, E16.4,
             5  / 7H STREAM, 16X, 2F16.4, 32X, F16.4,        F16.4/ 7H MOL WT,
             6  38X, F7.3, 28X, F7.3)
              WRITE (6,252) CYCLE, P0, P5, WA, WF
     252      FORMAT (7H CYCLE=, E13.6, 5X, 3HP0=, E13.6, 5X, 3HP5=, E13.6, 5X,
             1  3HWA=, E11.4, 5X, 3HWF=, E11.4)
     30       RETURN
              END
```

```
ION    AINLET                                        CDC 6600 FTN V3.0-251A OPT=1  07/15/7
          FUNCTION AINLET(A)
          LOGICAL  DUMPLOS, ETAF2, ETAFE,ACLOG
          COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,ND
          COMMON /BUMA/ AM3, CDB, Y4P
          COMMON /AINLT/ A1, AC, AE, ASTAR, AM0, AM1, AM3CK, DUMPLOS,
         1 ETAMIX, ETAF2, ETAFE, FAR, GAMT, INKT, P0, PT0, T0, TTF
          ACLOG = .FALSE.
          GO TO 1
          ENTRY BINLET
          ACLOG = .TRUE.
    1     AC=A
          INKT = INKT + 1
          X1 = AC*X(1.4,AM0)/A1
          AM1= XM(X1,1.4)
          P1 = PT0/PR(1.4,AM1)
          WA = P0*AC*AM0*SQRT((1.4*32.2*28.966)/(1545.264*T0))
          FA1 = PT0*A1*Z(1.4,AM1)
          WF = WA*FAR
          XSTAR = X(GAMT, 1.0)
          PTP = (WF*SQRT((TTF*1545.264)/(32.2*44.0)))/(ASTAR*XSTAR)
          PTH = PTP/PR(GAMT, 1.0)
          IF (PTH.LT.P1) GO TO 3
          XE = XSTAR*ASTAR/AE
          AME = SMX(XE,GAMT)
          FE = PTP*AE*Z(GAMT, AME)
          GO TO 4
    3     AME=WF/(P1*AE*SQRT(GAMT*32.2*44./(1545.264*TTF)))
          FE = P1*AE*(1.0+GAMT*(AME**2))
    4     F2 = FA1 + FE
          IF(ETAF2)  F2= ETAMIX*F2
          IF (ETAFE)  F2 = FA1 + ETAMIX*FE
          Y2 =((WA+WF)*SQRT(TT2*1545.264/(32.2*AWT)))/F2
          IF (.NOT. ACLOG) GO TO 10
          YCK = Y(GAM2, 1.0)
          AINLET = (1.0 -Y2/YCK)
          IF ((AINLET .GE. 0.0) .AND. (INKT .EQ. 1)) AINLET=0.0
          AINLET = AINLET*1.0E3
          GO TO 500
   10     AM2 = YM(Y2,GAM2)
          Z2 = Z(GAM2, AM2)
          X2 = X(GAM2, AM2)
          IF (DUMPLOS)  GO TO 5
          X3 = X2*A2/A3
          PT3 = ((WA+WF)*SQRT(TT2*1545.264/(32.2*AWT)))/(A3*X3)
          GO TO 6
    5     CALL DUMP (Z2, X3)
    6     AM3CK = XM(X3, GAM2)
          AINLET = (AM3 - AM3CK)/AM3
          IF ((AINLET .GE. 0.0) .AND. (INKT .EQ. 1)) AINLET=0.0
          AINLET = AINLET*1.0E2
  500     RETURN
          END
```

```
JTINE  DUMP                                          CDC 6600 FTN V3.0-251A OPT=1  07/15/71

      SUBROUTINE DUMP (Z2, X3)
C     COMPUTES DIFFUSER AND DUMP LOSSES
      COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,DND
      PT2 = F2/(A2*Z2)
      P2 = PT2/PR(GAM2,AM2)
      P3 = (0.5*CPR*GAM2*(AM2**2) + 1.0)*P2
      AONE = (GAM2-1.0)/2.0
      CONE = -(((WA+WF)**2)*1545.264*TT2)/((P3**2)*(A2P**2)*(GAM2*32.2
     1 *AWT))
      Q = SQRT(1.0-4.    NE*CONE)
      AM3P = (-1.0+Q)/(2.  AONE)
      IF((AM3P.LE.0.).OR.(AM3P.GE.1.))  AM3P = (-1.0-Q)/(2.0*AONE)
      AM3P = SQRT(AM3P)
      PT3 = P3*PR(GAM2,AM3P)
      PT3 = PT3*EXP(-0.5*DND*GAM2*AM3P**2)
      X3 = (WA+WF)*SQRT(1545.264*TT2/(32.2*AWT))/(PT3*A3)
      RETURN
      END
```

```
ION     BUMAC                                    CDC 6600 FTN V3.0-251A OPT=1  07/15/71

          FUNCTION BUMAC(A)
          COMMON /BUMA/ AM3, CDB, Y4P
          COMMON/DUM/ A2,A3,AWT,AM2,F2,GAM2,PT3,TT2,WA,WF,A2P,CPR,ND
          AM3 = A
          SQ = A**2
          BUMAC = Y4P*(1.0+GAM2*SQ*(1.0-CDB/2.0))/(SQRT(1.0+(GAM2-1.0)/2.0
         1 *SQ)) - A
          BUMAC = BUMAC*1.0E2
          RETURN
          END
```

UTINE PROPAN                                                    CDC 6600 FTN V3.0-251A OPT=1  07/15/71

```
      SUBROUTINE PROPAN (T, CP, HF)
      A = -0.966
      B = 7.279E-2
      C = -3.755E-5
      D = 7.58E-9
      CP = A + B*T + C*(T**2) + D*(T**3)
      TC = 300.0
      HCON = A*TC + 0.5*B*(TC**2) + C*(TC**3)/3.0 + 0.25*D*(TC**4)
      HF = A*T + 0.5*B*(T**2) + C*(T**3)/3.0 + 0.25*D*(T**4) - HCON
      RETURN
      END
```

CDC 6600 FTN V3.0-251A OPT=1 07/15/71

```
SUBROUTINE AIRTHR (T, CP, HA)
A = 6.386
B = 1.762E-3
C = -2.656E-7
CP = A + B*T + C*(T**2)
TC = 300.0
HCON = A*TC + 0.5*B*(TC**2) + C*(TC**3)/3.0
HA = A*T + 0.5*B*(T**2) + C*(T**3)/3.0 - HCON
RETURN
END
```

```
      SUBROUTINE ATMOS(Z,TM,SIGMA,RHO,THETA,DELTA,CA,AMU,K)
C     CALLING SEQUENCE
C     CALL ATMOS(Z,TM,SIGMA,RHO,THETA,DELTA,CA,AMU,K)
C     Z     = GEOMETRIC ALTITUDE (FT)
C     TM    = MOLECULAR SCALE TEMPERATURE (DEGREES RANKIN)
C     RHO   = DENSITY LB-SEC**2-FT**(-4) OR SLUGS-FT**3
C     THETA = RATIO OF TEMPERATURE TO THAT AT SEA LEVEL
C     DELTA = RATIO OF PRESSURE TO THAT AT SEA LEVEL
C     CA    = SPEED OF SOUND (FT/SEC)
C     AMU   = VISCOSITY COEFFICIENT (LB-SEC-FT**2)
C     K = 1 NORMAL,
C       = 2 ALTITUDE GREATER THAN 300000. FT.,
C       = 3 ALTITUDE NEGATIVE,
      DIMENSION HPRIMB(11),TMB(11),SIGMAB(11),ALM(11),ARAY(11,4)
      EQUIVALENCE (ARAY(1,1),HPRIMB(1)),(ARAY(1,2),TMB(1)),
     *            (ARAY(1,3),SIGMAB(1)),(ARAY(1,4),ALM(1))
      DATA ((ARAY(I,J),J=1,4),I=1,11)/
     X         0.    ,     518.688 ,   1.0000000E 00 ,   -0.00356616 ,
     X     36089.239 ,     389.988 ,   2.9706958E-01 ,    0.         ,
     X     82020.997 ,     389.988 ,   3.2665751E-02 ,    0.00164592 ,
     X    154199.480 ,     508.788 ,   1.2117870E-03 ,    0.         ,
     X    173884.510 ,     508.788 ,   5.8677311E-04 ,   -0.00246888 ,
     X    259186.350 ,     298.188 ,   1.7329156E-05 ,    0.         ,
     X    295275.590 ,     298.188 ,   1.7928595E-06 ,    0.00219456 ,
     Y    344488.190 ,     406.188 ,   9.3921519E-08 ,    0.01097280 ,
     X    524974.380 ,    2386.188 ,   7.7658593E-10 ,    0.00548640 ,
     X    557742.780 ,    2566.188 ,   5.6324877E-10 ,    0.00274320 ,
     X    656167. 80 ,    2836.188 ,   2.5726771E-10 ,    0.001 2024 /
      DATA      Q    /  0.01874 176    / ,      RE   /  2.0855531E 07    /,
     X          S    /  198.72         / ,      PZ   /  2116.2           /,
     X       AMUZ    /  3.7372998E-07  / ,    RHOZ   /  0.0023769        /,
     X        TMZ    /  518.688        /
      K=1
      IF(Z)26,18,17
   26 K=3
      GO TO 13
   17 IF(Z.GT.300000.)  K=K+1
   18 HPRIM=(RE/(RE+Z))*Z
    9 DO 10 M=1,11
      IF(HPRIM-HPRIMB(M))11,12,10
   10 CONTINUE
      M=12
   11 M=M-1
   12 IF(ALM(M))14,15,14
   14 TM=TMB(M)+ALM(M)*(HPRIM-HPRIMB(M))
      SIGMA=EXP((1.0+(Q/ALM(M)))*(ALOG(TMB(M)/TM)))*SIGMAB(M)
      GO TO 20
```

UTINE ATMOS CDC 6600 FTN V3.0-251A OPT=1 07/15/71

```
 15   TM=TMB(M)
      SIGMA=SIGMAB(M)*EXP(-(Q*(HPRIM-HPRIMB(M))'/TMB(M))
 20   RHO=RHOZ*SIGMA
      THETA=TM/TMZ
      DELTA=SIGMA*THETA
      CA=49.02177*SQRT(TM)
      AMU=AMUZ*SQRT(THETA**3)*((TMZ+S)/(TM+S))                ATMOS064
 13   RETURN                                                  ATMOS065
      END                                                     ATMOS066
```

```
      FUNCTION ATKN(X,Y,N,K,XI)
C
C     ATKN      AITKEN INTERPOLATING FUNCTION
C
C     USAGE...
C
C     Z=ATKN(X,Y,N,K,XI)
C
C       WHERE...
C
C         X - TABLE OF INDEPENDENT VARIABLE VALUES,
C              (MAY BE ASCENDING OR DESCENDING).
C         Y - TABLE OF DEPENDENT VARIABLE VALUES.
C         N - NO. OF POINTS IN TABLES X AND Y.
C         K - DEGREE OF INTERPOLATION DESIRED.
C         XI- X-VALUE FOR WHICH INTERPOLATION IS DESIRED.
C
C         THE INTERPOLATED VALUE IS RETURNED AS THE FUNCTION VALUE.
C
C         31 CELLS OF BLANK COMMON ARE USED.
C
      DIMENSION    X(N), Y(N)
      COMMON    I1, K1, LI, LL, LU
      COMMON    XX(13), YY(13)
      DATA    KMAX/ 12/
C
      IF ( K .GT. KMAX .OR. K .LE. 0 )      GO TO 300
C
      K1=K+1
      IF (X(N)-X(1)) 100,10,10
   10 IF (XI-X(1)) 20,20,30
   20 LL=0
      GO TO 200
   30 IF (X(N)-XI) 40,40,50
   40 LL=N-K1
      GO TO 200
   50 LL=1
      LU=N
   60 IF (LU-LL-1) 180,180,70
   70 LI=(LL+LU)/2
      IF (X(LI)-XI) 80,80,90
   80 LL=LI
      GO TO 60
   90 LU=LI
      GO TO 60
  100 IF (XI-X(1)) 120,20,20
  120 IF (X(N)-XI) 130,40,40
  130 LL=1
      LU=N
  140 IF (LU-LL-1) 180,180,150
  150 LI=(LL+LU)/2
      IF (X(LI)-XI) 160,170,170
  160 LU=LI
      GO TO 140
  170 LL=LI
```

```
ION      ATKN                                          CDC 6600 FTN V3.0-251A OPT=1   07/15/71

            GO TO 140
        180 LL=LL-(K1+1)/2
            IF (LL) 20,700,190
        190 IF (LL+K1-N) 200,200,40
        200 DO 210 I=1,K1
            I1=LL+I
            XX(I)=X(I1)-XT
        210 YY(I)=Y(I1)
            DO 220 I=1,K
            DO 220 J=I,K
        220 YY(J+1)=(1./(XX(J+1)-XX(I)))*(YY(I)*XX(J+1)-YY(J+1)*XX(I))
            ATKN=YY(K1)
            RETURN
      C
        700 PRINT 1000, K
       1000 FORMAT (4H0K=,I12,33H   IS INCORRECT FOR FUNCTION ATKN)
            CALL SYSTEM(200.0)
            END
```

JTINE SOLNEW CDC 6600 FTN V3.0-251A OPT=1 07/15/71

```
      SUBROUTINE SOLNEW(FX, ALOW, HI, TRAP, Y)
C  SOLVES THE FUNCTION FX FOR THE VALUE OF THE INDEPENDENT VARIABLE X
C  WHICH MAKES THE VALUE OF FX EQUAL TO ZERO.  THE VALUE OF X MUST LIE
C  IN THE INTERVAL BOUNDED BY ALOW AND HI.  IF ANY FATAL DIFFICULTY IS
C  INCOUNTERED IN THE SOLUTION THE LOGICAL VARIABLE TRAP IS SET EQUAL
C  TO TRUE.
      EXTERNAL FX
      LOGICAL TRAP, FIRST
      DIMENSION F(4), X(4)
      TRAP = .FALSE.
      FIRST = .TRUE.
      TOL = 1.0E-4
      H = HI
      SMAL = ALOW
      IF (ALOW .LT. HI) GO TO 17
      H = ALOW
      SMAL = HI
   17 X(1) = ALOW
      F(1) = FX(X(1))
      Y = X(1)
      IF (ABS(F(1)) .LT. TOL)  GO TO 83
      X(3) = HI
      F(3) = FX(X(3))
      Y = X(3)
      IF (ABS(F(3)) .LT. TOL)  GO TO 83
      Z = SIGN(F(1), F(3))
      IF ((F(1)+Z) .EQ. 0.0)  GO TO 32
      WRITE (6,28)
   28 FORMAT (60H THE FUNCTIONS FOR THE END POINTS DO NOT HAVE OPPOSITE
     1SIGNS)
      TRAP = .TRUE.
      GO TO 83
   32 X(2) = X(1) - F(1)*(X(3) - X(1))/(F(3)- F(1))
      F(2) = FX(X(2))
      Y = X(2)
      IF (ABS(F(2)) .LT. TOL)  GO TO 83
      DO 69  JK=1,9
      X1SQ = X(1)**2
      X1X2 = X(1) - X(2)
      X1X3 = X(1) - X(3)
      X2X1SQ = X(2)**2 - X(1)**2
      A = X1X3*(F(2)-F(1)) - X1X2*(F(3)-F(1))
      A = A/(X1X3*X2X1SQ - X1X2*(X(3)**2 - X1SQ))
      B = (A*X2X1SQ - F(2) + F(1))/X1X2
      C = F(3) - A*(X(3)**2) - B*X(3)
      Q = SQRT(B**2 - 4.0*A*C)
      X(4) = (-B+Q)/(2.0*A)
      IF((X(4).GT.H).OR.(X(4).LT.SMAL)) X(4)=(-B-Q)/(2.0*A)
      Y = X(4)
      IF (JK .EQ. 9) GO TO 70
      F(4) = FX(X(4))
      IF (ABS(F(4)) .LT. TOL)  GO TO 83
      DO 62   I=1,3
      I1 = I+1
      DO 62   J=I1,4
```

```
      IF (F(I) .LE. F(J))  GO TO 62
      FS = F(I)
      XS = X(I)
      F(I) = F(J)
      X(I) = X(J)
      F(J) = FS
      X(J) = XS
 62   CONTINUE
      IF (.NOT. FIRST)  GO TO 63
      IF ((F(1) + F(2)) .LE. F(1))  GO TO 100
      XN = (2.0*X(2) + X(1))/3.0
      FN = FX(XN)
      IF ((F(1) + FN) .LE. F(1)) GO TO 110
      F(2) = FN
      X(2) = XN
      GO TO 63
 100  IF ((F(3) + F(4)) .GE. F(4))  GO TO 63
      XN = (X(4) + 2.0*X(3))/3.0
      FN = FX(XN)
      IF ((F(4) + FN) .GE. F(4))  GO TO 115
      F(3) = FN
      X(3) = XN
      GO TO 63
 110  F(1) = FN
      X(1) = XN
      GO TO 63
 115  F(4) = FN
      X(4) = XN
 63   FIRST = .FALSE.
      IF (ABS(F(1)) .GT. ABS(F(4)))  GO TO 68
      IF ((F(3)+F(4)) .GE. F(4))  GO TO 69
 65   F(1) = F(4)
      X(1) = X(4)
      GO TO 69
 68   IF ((F(1)+F(2)) .LE. F(1))  GO TO 65
 69   CONTINUE
 70   DO 82   I=1,5
      FY = FX(Y)
      IF (ABS(FY) .LT. TOL)  GO TO 83
      XLIT = Y + 0.01*TOL*Y
      FLIT = FX(XLIT)
      XD = Y - XLIT
      FD = FY- FLIT
      DIR = FD/XD
      IF (DIR .NE. 0.0)  GO TO 81
      TRAP = .TRUE.
      GO TO 83
 81   Y = Y - FY/DIR
 82   CONTINUE
      WRITE (6,85)
 85   FORMAT (24H SOLNEW DID NOT CONVERGE)
      TRAP = .TRUE.
 83   RETURN
      END
```

ION X CDC 6600 FTN V3.0-251A OPT=1 07/15/71

```
      FUNCTION  X(G, A)
C  DETERMINES  X  AS A FUNCTION OF MACH NUMBER.   G=GAMMA, A=MACH NO.
      G1 = G - 1.0
      X = A*SQRT(G/((1.0+0.5*G1*(A**2))**((G+1.0)/G1)))
      RETURN
      END
```

:ON Y CDC 6600 FTN V3.0-251A OPT=1 07/15/71

```
      FUNCTION  Y(G, A)
C  DETERMINES  Y  AS A FUNCTION OF MACH NUMBER.  G=GAMMA, A=MACH NO.
      SQ = A**2
      Y = (A/(1.0+G*SQ))*SQRT(G*(1.0+0.5*(G-1.0)*SQ))
      RETURN
      END
```

```
ON    Z                                        CDC 6600 FTN V3.0-231A OPT=1  07/15/7

          FUNCTION  Z(G, A)
      C  DETERMINES  Z  AS A FUNCTION OF MACH NUMBER.   G=GAMMA, A=MACH NO.
          SQ = A**2
          G1 = G - 1.0
          Z = (1.0+G*SQ)/((1.0+0.5*G1*SQ)**(G/G1))
          RETURN
          END
```

JTINE FUELDAT CDC 6600 FTN V3.0-251A OPT=1 07/15/71

```
      SUBROUTINE FUELDAT (T0, FAR, DT, WTH4, GAM4)
      DIMENSION TEMS(12), FARS(18), Z1(18,12), Z2(18,12), Z3(18,12)
      READ (5,2)  NFAR, NT
2     FORMAT (2I10)
      READ (5,5) (FARS(I), I=1,NFAR)
      READ (5,5)  (TEMS(I), I=1,NT)
5     FORMAT (10X, 6E10.0)
      DO 10  K=1,NT
10    READ (5,5)  (Z1(I,K)  I=1,NFAR)
      DO 20  K=1,NT
20    READ (5,5)  (Z2(I,K), I=1,NFAR)
      DO 30  K=1,NT
30    READ (5,5)  (Z3(I,K), I=1,NFAR)
      RETURN
      ENTRY FUELINT
      DT   = BUYIN(FAR, T0, FARS, NFAR, TEMS, NT, Z1)
      WTH4 = BUYIN(FAR, T0, FARS, NFAR, TEMS, NT, Z2)
      GAM4 = BUYIN(FAR, T0, FARS, NFAR, TEMS, NT, Z3)
      RETURN
      END
```

```
[ON     9UYIN                                        CDC 6500 FTN V3.0-251A OPT=1  07/15/7:
           FUNCTION BUYIN (XI, YI, X, NX, Y, NY, Z)
           DIMENSION X(18), Y(12), Z(18,12), V(18), U(12)
           DO 6  I=1,NY
           DO 5  J=1,NX
     5     V(J) = Z(J,I)
     6     U(I) = ATKN (X, V, NX,  1, XI)
           BUYIN = ATKN (Y, U, NY, 1, YI)
           RETURN
           END
```

```
      FUNCTION XM(X,G)
C  DETERMINES SUBSONIC MACH NUMBER AS A FUNCTION OF X.  G=GAMMA
      TOL = X*1.0E-8
      G1 = G-1.0
      XM = 0.0
      F1 = -X
      IF(ABS(F1) .LE. TOL)  GO TO 26
      XM = 1.0
      F3 = SQRT(G/((1.0+0.5*G1)**((G+1.0)/G1))) - X
      IF(ABS(F3) .LT. TOL)  GO TO 26
      SI = SIGN(F1, F3)
      IF ((F1 + SI) .EQ. 0.0) GO TO 13
      PRINT 100, F3
  100 FORMAT (30H SAME SIGN FOR X FUNCTION - F=, E13.5)
      XM = 1.0
      GO TO 26
   13 XM =-F1/(F3 - F1)
      F2 = XM*SQRT(G/((1.0+0.5*G1*(XM**2))**((G+1.0)/G1))) - X
      A = ((F3-F1)*XM - F2 + F1)/(XM*(1.0-XM))
      B = F3 - F1 - A
      C = F1
      RT = SQRT(B**2 - 4.0*A*C)
      XM = (-B+RT)/(2.0*A)
      IF((XM.GT.1.0) .OR. (XM.LT.0.0)) XM=(-B-RT)/(2.0*A)
      DO 25  I=1,9
      SQ = XM**2
      F = XM*SQRT(G/((1.0+0.5*G1*SQ)**((G+1.0)/G1))) - X
      IF(ABS(F) .LT. TOL) GO TO 26
      FP = 2.0*(1.0-SQ)*(SQRT(G/((1.0+0.5*G1*SQ)**((G+1.0)/G1))))
     1 /(2.0 + G1*SQ)
   25 XM = XM - F/FP
      PRINT 50
   50 FORMAT (23H X FUN DID NOT CONVERGE)
   26 RETURN
      END
```

```
      FUNCTION YM(Y,G)
C  DETERMINES SUBSONIC MACH NO. AS A FUNCTION OF Y.  G=GAMMA
      TOL = Y*1.0E-8
      G1 = G - 1.0
      YM = 0.0
      F1 = -Y
      IF (ABS(F1) .LE. TOL) GO TO 27
      YM = 1.0
      F3 = (SQRT(G*(1.0+0.5*G1)))/(1.0+G) - Y
      IF (ABS(F3) .LT. TOL)  GO TO 27
      YM =-F1/(F3 - F1)
      SQ = YM**2
      F2 = (YM/(1.0+G*SQ))*SQRT(G*(1.0+0.5*G1*SQ)) - Y
      A = ((F3-F1)*YM - F2 + F1)/(YM*(1.0-YM))
      B = F3 - F1 - A
      C = F1
      RT = SQRT(B**2 - 4.0*A*C)
      YM = (-B+RT)/(2.0*A)
      IF ((YM.LT.0.0) .OR. (YM.GT.1.0)) YM=(-B-RT)/(2.0*A)
      DO 26  I=1,9
      SQ = YM**2
      F = (YM/(1.0+G*SQ))*SQRT(G*(1.0+0.5*G1*SQ)) - Y
      IF (ABS(F) .LT. TOL) GO TO 27
      FP = ((1.0-SQ)/(1.0+0.5*G1*SQ))*(SQRT(G*(1.0+0.5*G1*SQ)))/
     1 ((1.0+G*SQ)**2)
   26 YM = YM - F/FP
      PRINT 50
   50 FORMAT (23H Y FUN DID NOT CONVERGE)
   27 RETURN
      END
```

```
      FUNCTION ZM(Z,G)
C  DETERMINES SUBSONIC MACH NUMBER AS A FUNCTION OF Z.  G=GAMMA
      TOL = Z*1.0E-9
      G1 = G - 1.0
      ZM = 0.0
      F1 = 1.0 - Z
      IF(ABS(F1) .LT. TOL)  GO TO 26
      ZM = 1.0
      F3 = (1.0+G)/((1.0+0.5*G1)**(G/G1)) - Z
      IF(ABS(F3) .LT. TOL) GO TO 26
      ZM = F1/(F3 - F1)
      SQ = ZM**2
      F2 = (1.0 + G*SQ)/((1.0+0.5*G1*SQ)**(G/G1)) - Z
      A = ((F3-F1)*ZM - F2 + F1)/(ZM-SQ)
      B = F3 - F1 - A
      C = F1
      RT = SQRT(B**2 - 4.0*A*C)
      ZM = (-B + RT)/(2.0*A)
      IF((ZM.GT.1.0).OR.(ZM.LT.0.0)) ZM=(-B-RT)/(2.0*A)
      DO 25   I=1,10
      SQ = ZM**2
      F = (1.0+G*SQ)/((1.0+0.5*G1*SQ)**(G/G1)) - Z
      IF (ABS(F) .LT. TOL) GO TO 26
      FP=G*ZM*(2.-(1.+G*SQ)/(1.+.5*G1*SQ))/((1.+.5*G1*SQ)**(G/G1))
25    ZM = ZM - F/FP
      PRINT 50
50    FORMAT (23H Z FUN DID NOT CONVERGE)
26    RETURN
      END
```

```
      FUNCTION SMX(X,G)
C DETERMINES SUPERSONIC MACH NO. AS A FUNCTION OF X. G=GAMMA, MAX MACH=4
      DIMENSION  FA(3), XA(3)
      TOL = X*1.0E-5
      G1 = G - 1.0
      XA(1) = 1.0
      XA(2) = 4.0
      DO 13   I=1,3
      FA(I)=XA(I)*SQRT(G/((1.+.5*G1*(XA(I)**2))**((G+1.)/G1)))-X
      SMX = XA(I)
      IF(ABS(FA(I)) .LT. TOL) GO TO 32
      IF(I.EQ.2) XA(3)=XA(1)-FA(1)*(XA(2)-XA(1))/(FA(2)-FA(1))
   13 CONTINUE
      X1SQ = XA(1)**2
      X1X2 = XA(1) - XA(2)
      X1X3 = XA(1) - XA(3)
      X2X1SQ = XA(2)**2 - XA(1)**2
      A = X1X3*(FA(2) - FA(1)) - X1X2*(FA(3)-FA(1))
      A = A/(X1X3*X2X1SQ - X1X2*(XA(3)**2 - X1SQ))
      B = (A*X2X1SQ - FA(2) + FA(1))/X1X2
      C = FA(3) - A*(XA(3)**2) - B*XA(3)
      Q = SQRT(B**2 - 4.0*A*C)
      SMX = (-B+Q)/(2.0*A)
      IF((SMX.LT.1.0) .OR. (SMX.GT.4.0)) SMX=(-B-Q)/(2.0*A)
      DO 31   I=1,5
      SQ = SMX**2
      F = SMX*SQRT(G/((1.0+0.5*G1*SQ)**((G+1.0)/G1))) - X
      IF (ABS(F) .LT. TOL)  GO TO 32
      FP = 2.0*(1.0-SQ)*(SQRT(G/((1.0+0.5*G1*SQ)**((G+1.0)/G1))))/(2.0+
     1 G1*SQ)
   31 SMX = SMX - F/FP
   32 RETURN
      END
```

ION PR CDC 6600 FTN V3.0-251A OPT=1 07/15/71

```
      FUNCTION PR(G,A)
C  DETERMINES THE RATIO OF TOTAL PRESSURE TO STATIC PRESSURE AS A
C   FUNCTION OF MACH NO. AND GAMMA.    G=GAMMA,  A=MACH NO.
      G1 = G-1
      PR = (1.0 + 0.5*G1*(A**2))**(G/G1)
      RETURN
      END
```

```
ION    TR                                   CDC 6600 FTN V3.0-251A OPT=1  07/15/71

          FUNCTION TR(G,A)
C   DETERMINES THE RATIO OF TOTAL PRESSURE TO STATIC PRESSURE AS A
C      FUNCTION OF MACH NO. AND GAMMA.  G=GAMMA,  A=MACH NO.
          TR = 1.0 + 0.5*(G-1.0)*(A**2)
          RETURN
          END
```

```
CORE MAP  08.56.31.  NORMAL
        ---TIME---LOAD MODE  --L1--L2-----TYPE---------------USER---++---CALL
                                       CONTROL
        FWA LOADER  040764  FWA TABLES  035722
        -PROGRAM----ADDRESS-
        MOMCRJ       000152                      --LABELED---COMMON--
                                                            CYCL     000100
                                                            BUMA     000110
                                                            AINLT    000113
        CYCLE        003511                                 DUM      000135
                                                            CYCL     000100
                                                            BUMA     000110
                                                            AINLT    000113
        AINLET       004365                                 DUM      000135
                                                            DUM      000135
                                                            BUMA     000110
        DUMP         004673                                 AINLT    000113
        BUMAC        005005                                 DUM      000135
                                                            BUMA     000110
        PROPAN       005036                                 DUM      000135
        AIRTHR       005124
        ATMOS        005171
        ATKN         005363
        SOLNEW       005616
        X            006265
        Y            006310
        Z            006334
        FUELDAT      006350
        BUYIN        010010
        XM           010147
        YM           010371
        ZM           010570
        SMX          010766
        TR           011213
        PR           011231
        GETBA        011253
        SIO$         011272
        SYSTEM$      012646
        IFENDF$      013631
        INPUTC$      013710
        INPUTN$      014026
        KODER$       015205
        KRAKER$      016601
        OUTPTC$      020325
        ALNLOGE      020421
        EXPE         020460
        SQRTE        020524
        XTOYE        020546
        ----UNSATISFIED EXTERNALS-----                         REFERENCES
```

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